About SSA in hadronic interactions

TMDs and SSA in inclusive hadronic interactions

TMDs and SSA in Drell-Yan processes

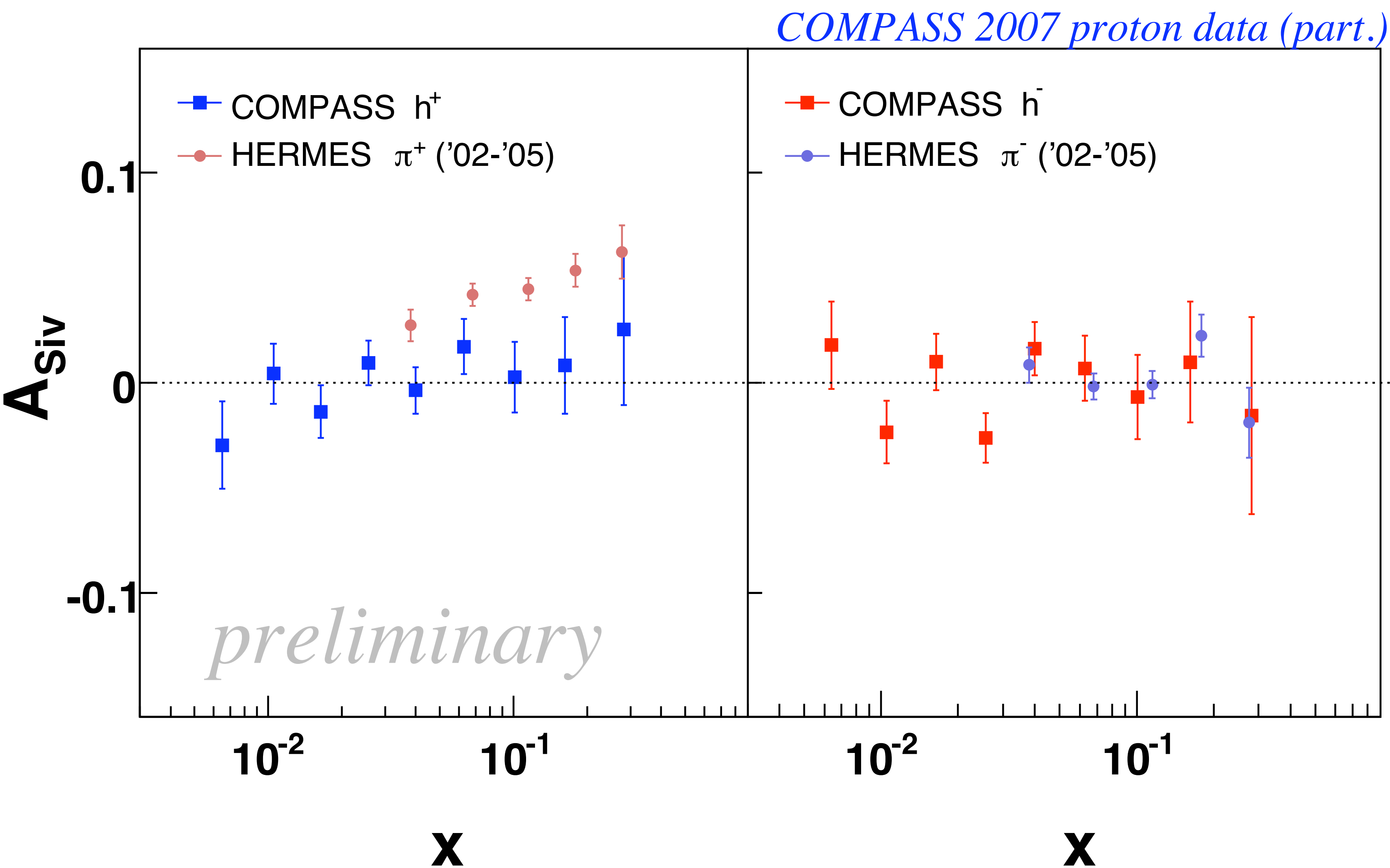
A fundamental QCD test

Drell-Yan processes, the transversity golden channel

Alternative ways to transversity

Sivers asymmetry: COMPASS vs HERMES

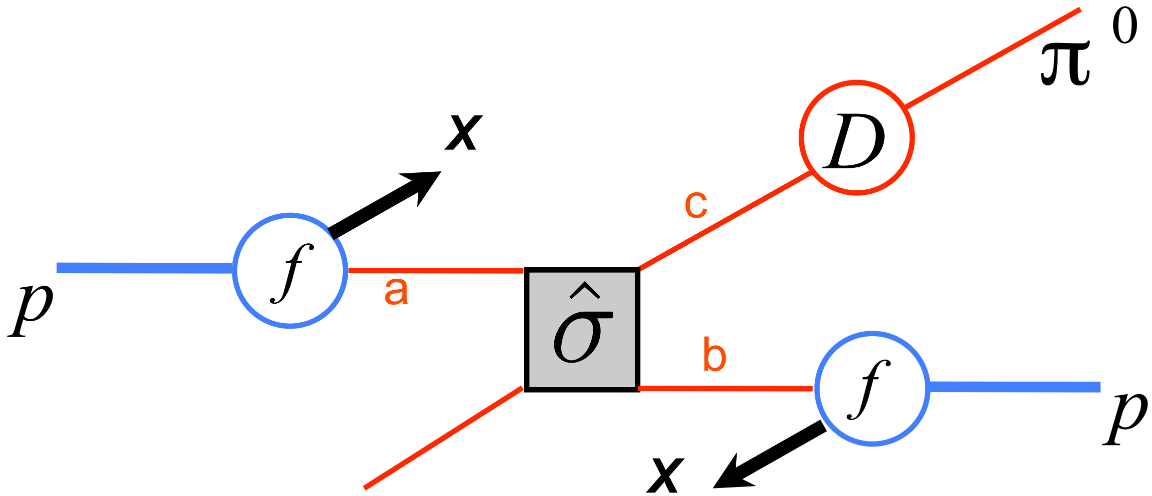
(F. Bradamante talk at Beijing workshop 2008)



TMDs and SSAs in hadronic collisions

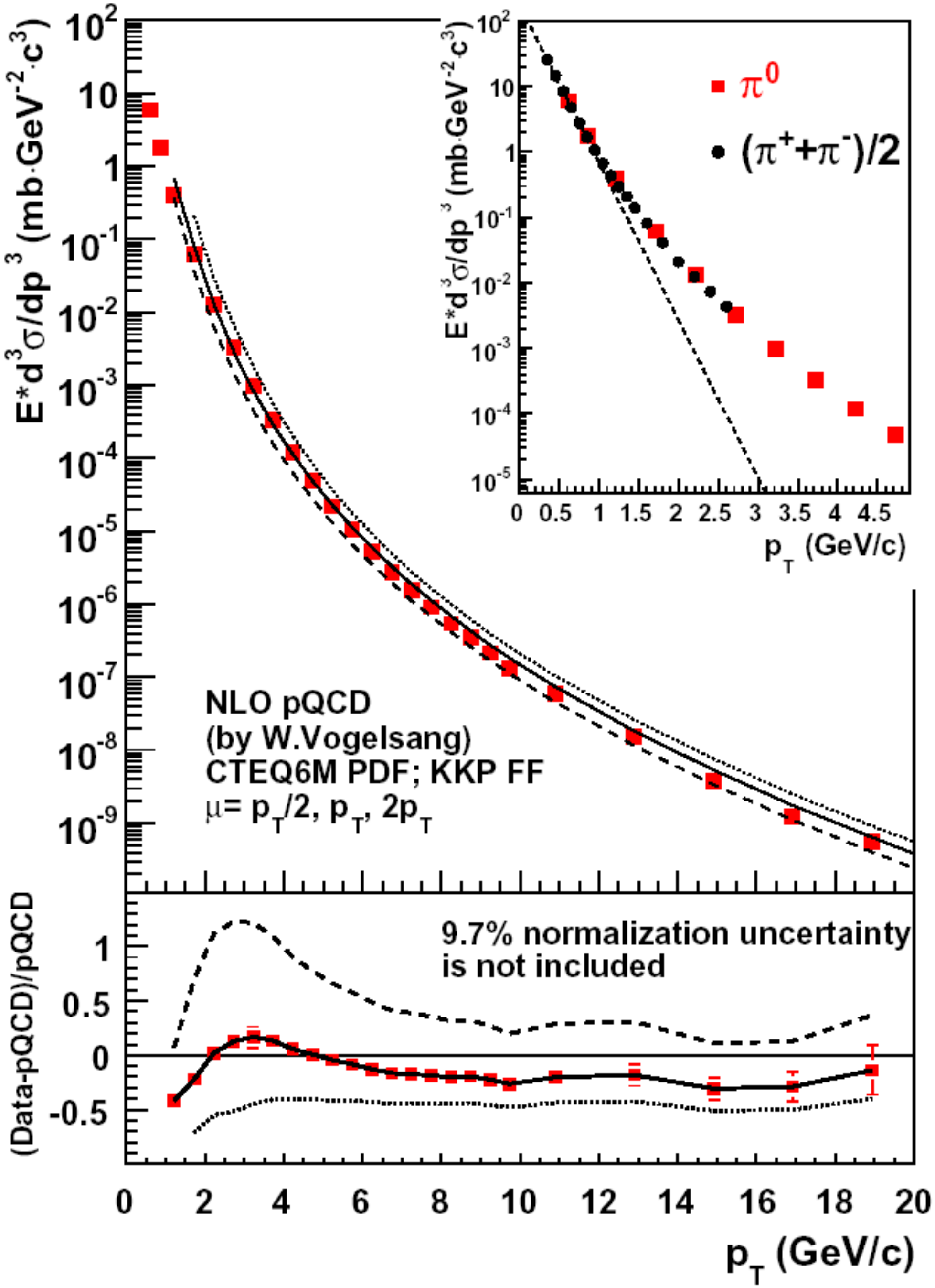
$$p\,p \longrightarrow \pi^0\,X$$ (collinear configurations)

factorization theorem



$$\mathrm{d}\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

pQCD elementary interactions

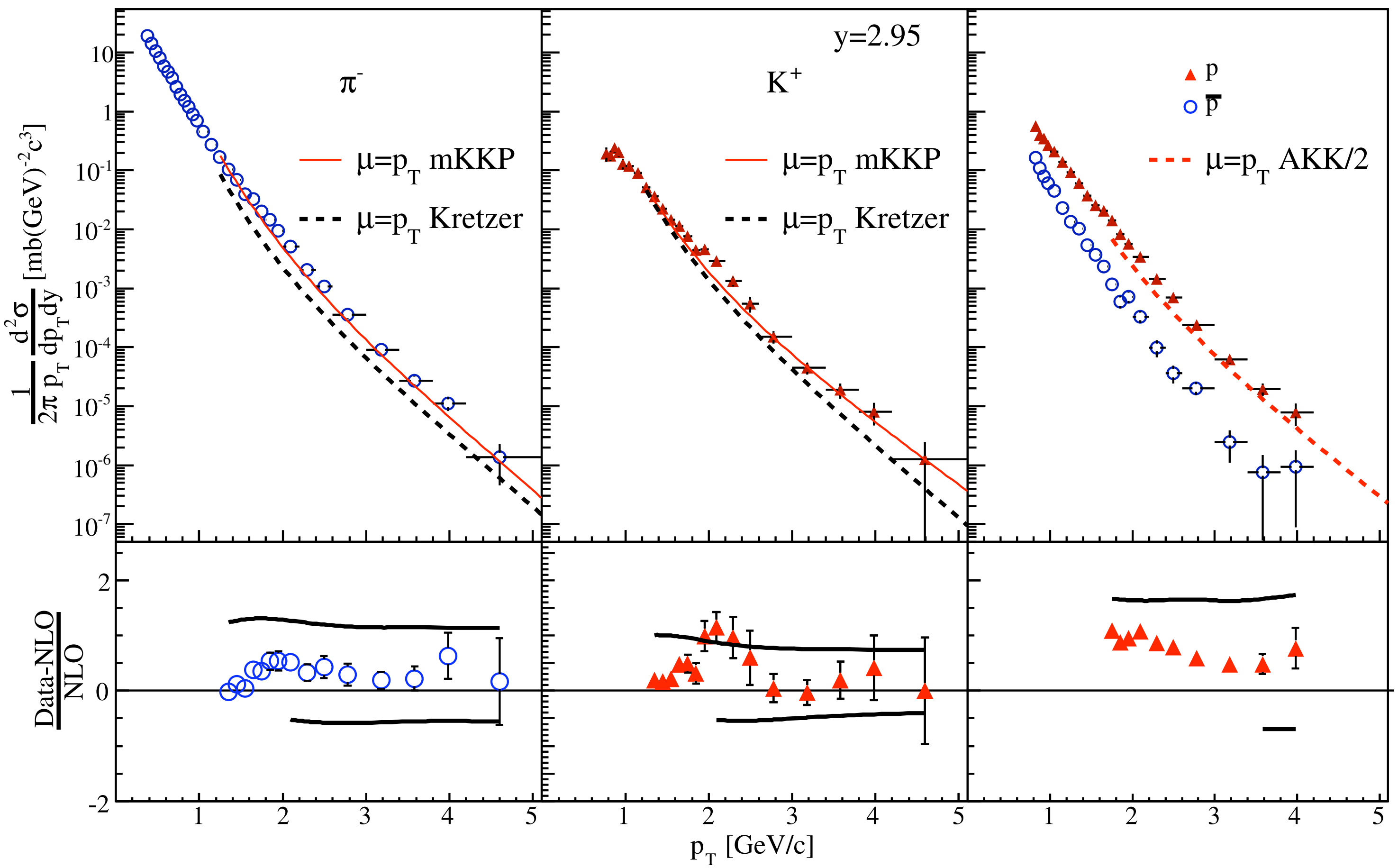


RHIC, $p\,p \to \pi\,X$

$\sqrt{s} = 200\,\text{GeV}$

PHENIX data on unpolarized cross section

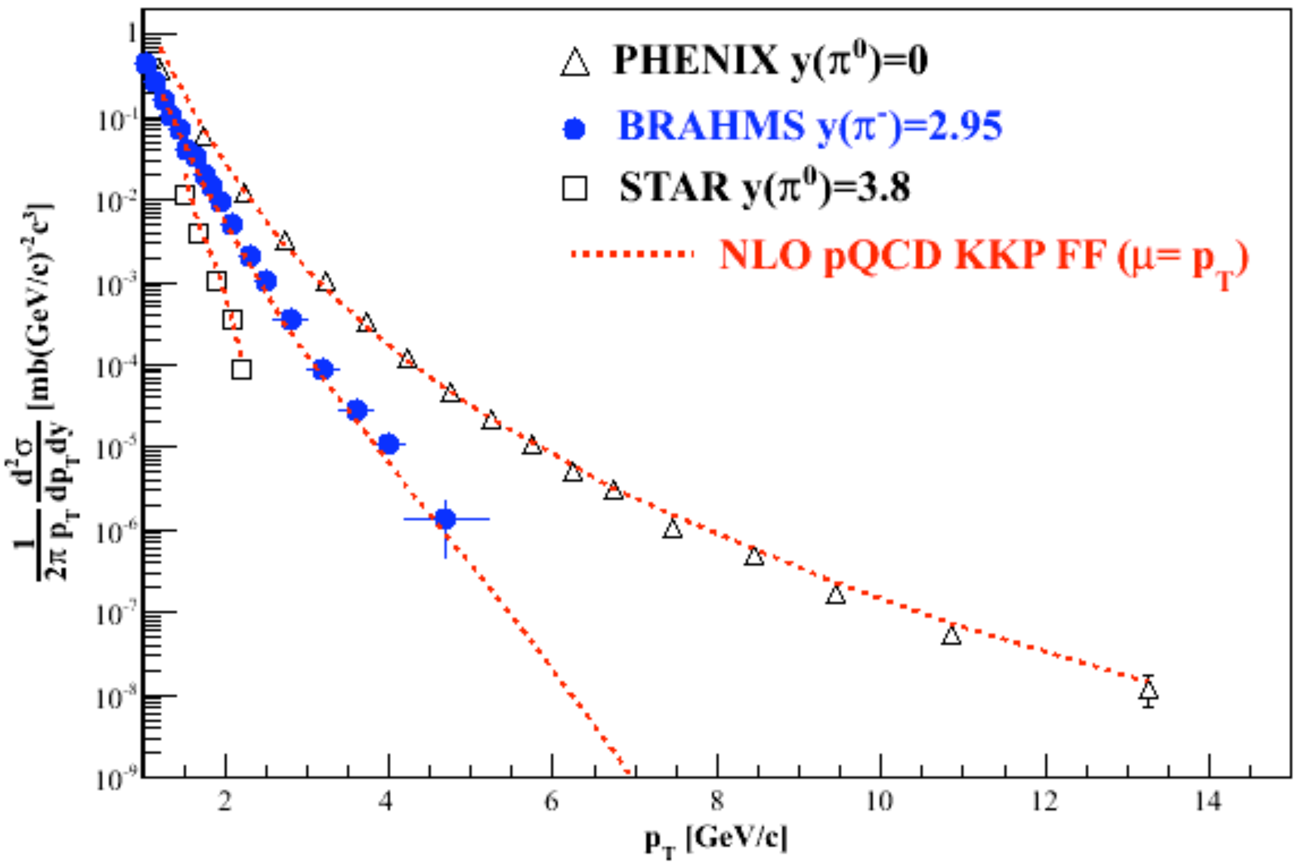
BRAHMS, proton-proton at 200 GeV



Phys. Rev. Lett. 98, 252001 (2007)

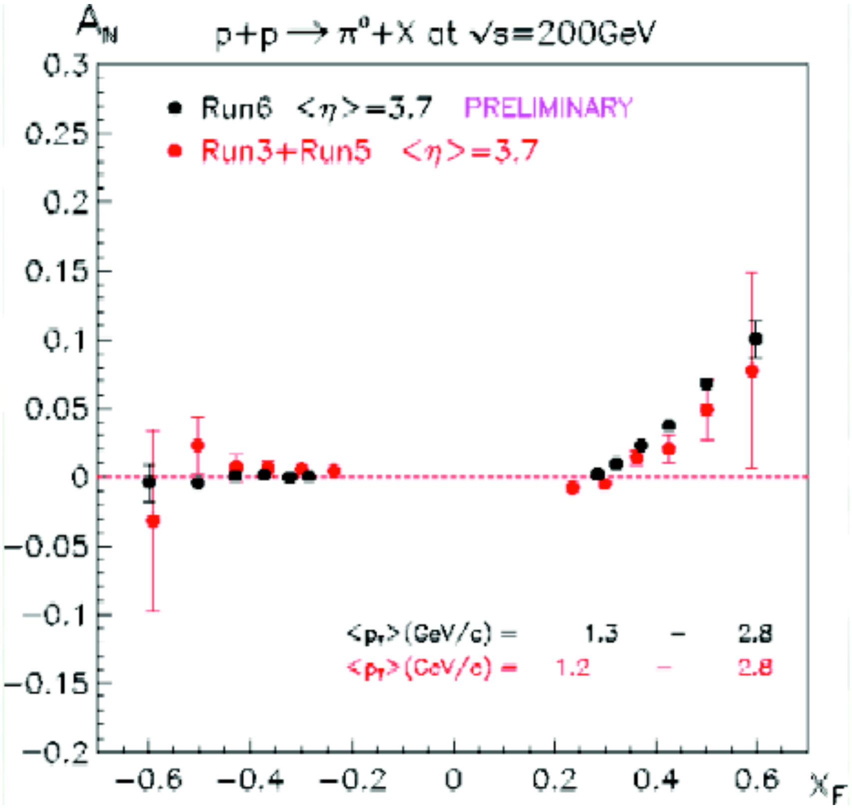
Polarization-averaged cross sections at $\sqrt{s}$=200 GeV

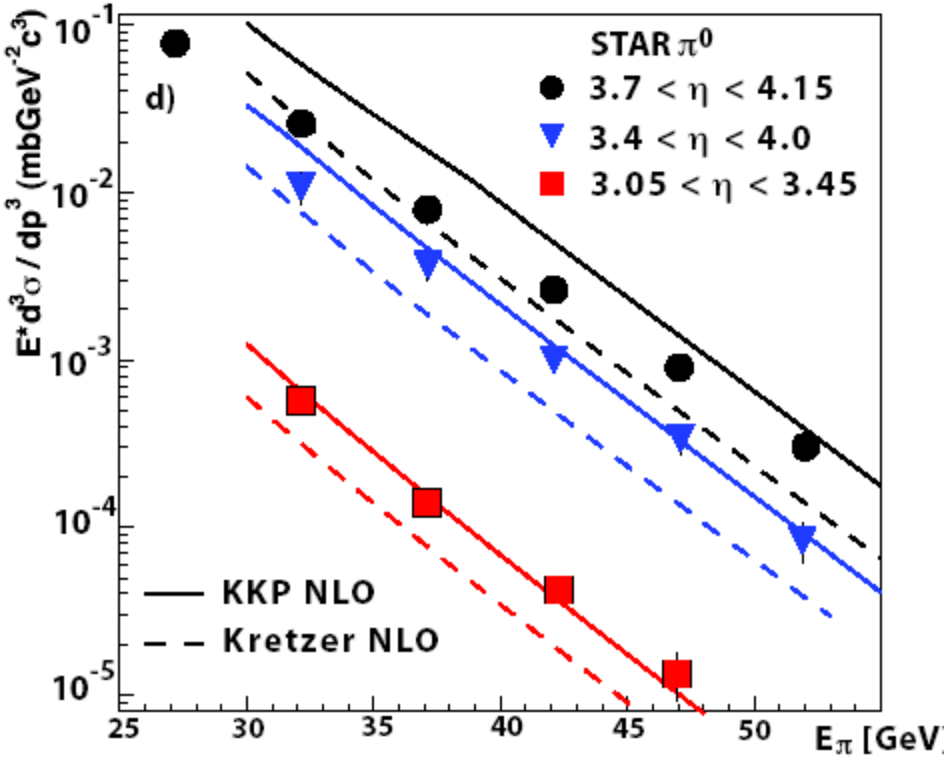
(talk of C. Aidala at Transversity 2008, May 2008, Ferrara)



good pQCD description of data at 200 GeV, at all rapidities, down to p_T of 1-2 GeV/c

but problems with SSAs ...

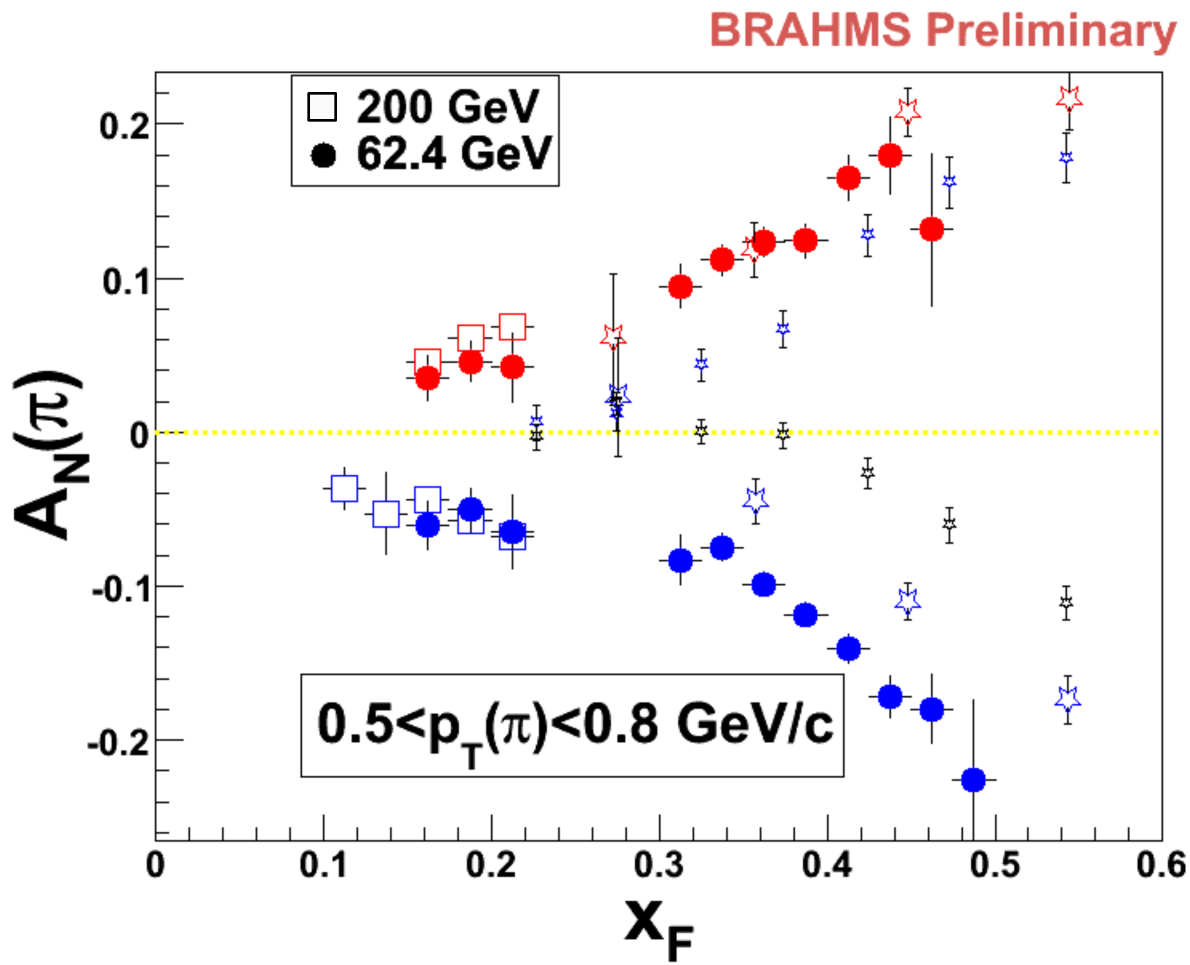




STAR-RHIC $\sqrt{s}$ = 200 GeV $1.2 < p_T < 2.8$

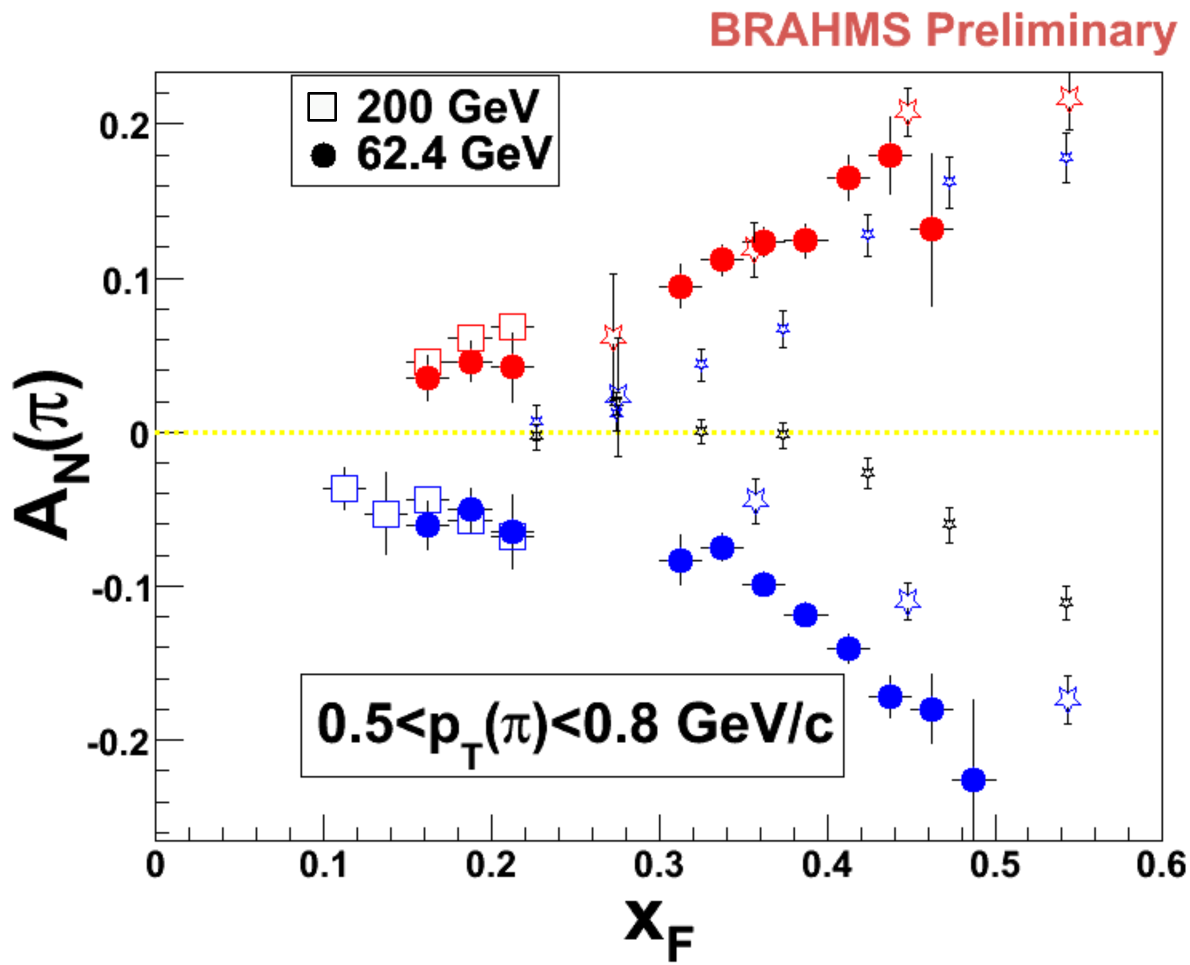
Unifying 62.4 and 200 GeV, BRAHMS + E704

(C. Aidala talk at transversity 2008, Ferrara)



Unifying 62.4 and 200 GeV, BRAHMS + E704

(C. Aidala talk at transversity 2008, Ferrara)

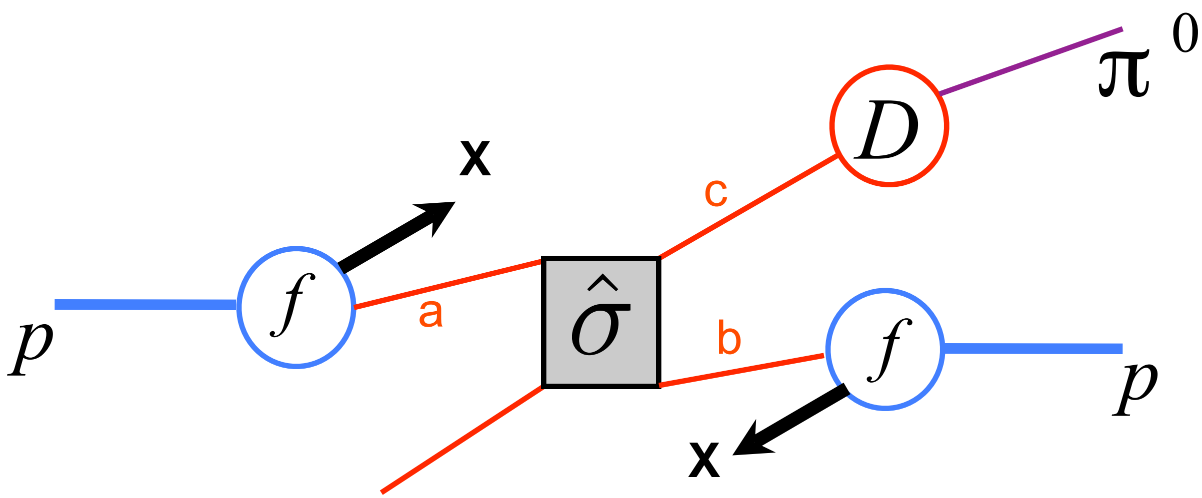


E704 data – all p_T (small stars); p_T>0.7 GeV/c (large stars)

SSA in hadronic processes: intrinsic $k_\perp$, factorization?

Two main different (?) approaches

Generalization of collinear scheme
(assuming factorization)



$$d\sigma = \sum_{a,b,c=q,\bar{q},g} f_{a/p}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes D_{\pi/c}(z, \boldsymbol{p}_{\perp\pi})$$

first proposed by Field-Feynman

Possible sources of SSA, simple approach
(one $\mathbf{k}_\perp$ at a time)

$$
\begin{aligned}
\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\uparrow} \quad = \quad & \sum_{a,b,c} \Big\{ \Delta^N f_{a/p^\uparrow}(\boldsymbol{k}_\perp) \otimes f_{b/p} \otimes \mathrm{d}\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \\
& + \; h_1^{a/p} \otimes f_{b/p} \otimes \mathrm{d}\Delta\hat{\sigma}(\boldsymbol{k}_\perp) \otimes \Delta^N D_{\pi/c^\uparrow}(\boldsymbol{k}_\perp) \\
& + \; h_1^{a/p} \otimes \Delta^N f_{b^\uparrow/p}(\boldsymbol{k}_\perp) \otimes \mathrm{d}\Delta'\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \Big\}
\end{aligned}
$$

(1) Sivers effect

(2) transversity $\otimes$ Collins

(3) transversity $\otimes$ Boer - Mulders

partially suppressed by phases

General formalism with helicity amplitudes

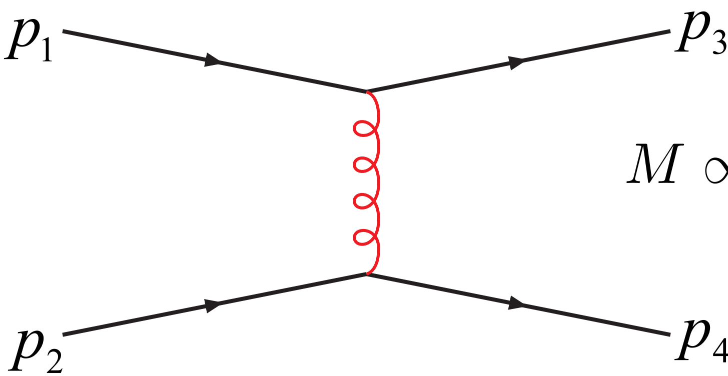
$$\mathrm{d}\sigma^{(A,S_A)+(B,S_B)\to C+X} = \sum \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \otimes \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\,\hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b})$$
$$\otimes \underbrace{\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\,\hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b}}_{\text{non planar process, plenty of phases}}(\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b})\,\hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

main (maybe) contribution to SSA from Sivers effect

$$\mathrm{d}\Delta\sigma^{p,S+p\to\pi+X} = \sum_q \Delta^N f_{q/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b,\boldsymbol{k}_{\perp b})$$
$$\otimes \quad \mathrm{d}\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b}) \otimes D_{\pi/c}(z,\boldsymbol{p}_{\perp\pi})$$

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia,
PR **D71**, 014002 (2005), PR **D73**, 014020 (2006)

Computation of helicity amplitudes



$$M \propto \bar{u}(p_3, \lambda_3)\, \gamma^\mu \, u(p_1, \lambda_1)\, \bar{u}(p_4, \lambda_4)\, \gamma_\mu \, u(p_2, \lambda_2)$$

$$p_i = (p_i^0, \; \boldsymbol{p}_i)$$

Dirac-Pauli helicity spinors

$$u(p_i, \lambda_i) = \sqrt{p_i^0} \begin{pmatrix} 1 \\ \lambda_i \end{pmatrix} \chi_{\lambda_i}(\hat{\boldsymbol{p}}_i) \qquad \hat{\boldsymbol{p}}_i = (\sin\theta_i \cos\phi_i, \; \sin\theta_i \sin\phi_i, \; \cos\theta_i)$$

$$\chi_+(\hat{\boldsymbol{p}}_i) = \begin{pmatrix} \cos(\theta_i/2)\, e^{-i\Phi_i/2} \\ \\ \sin(\theta_i/2)\, e^{i\Phi_i/2} \end{pmatrix} \qquad \chi_-(\hat{\boldsymbol{p}}_i) = \begin{pmatrix} -\sin(\theta_i/2)\, e^{-i\Phi_i/2} \\ \\ \cos(\theta_i/2)\, e^{i\Phi_i/2} \end{pmatrix}$$

if scattering is not planar all phases are different and remain in the amplitudes; they suppress the results when integrating over $\mathbf{k}_\perp$

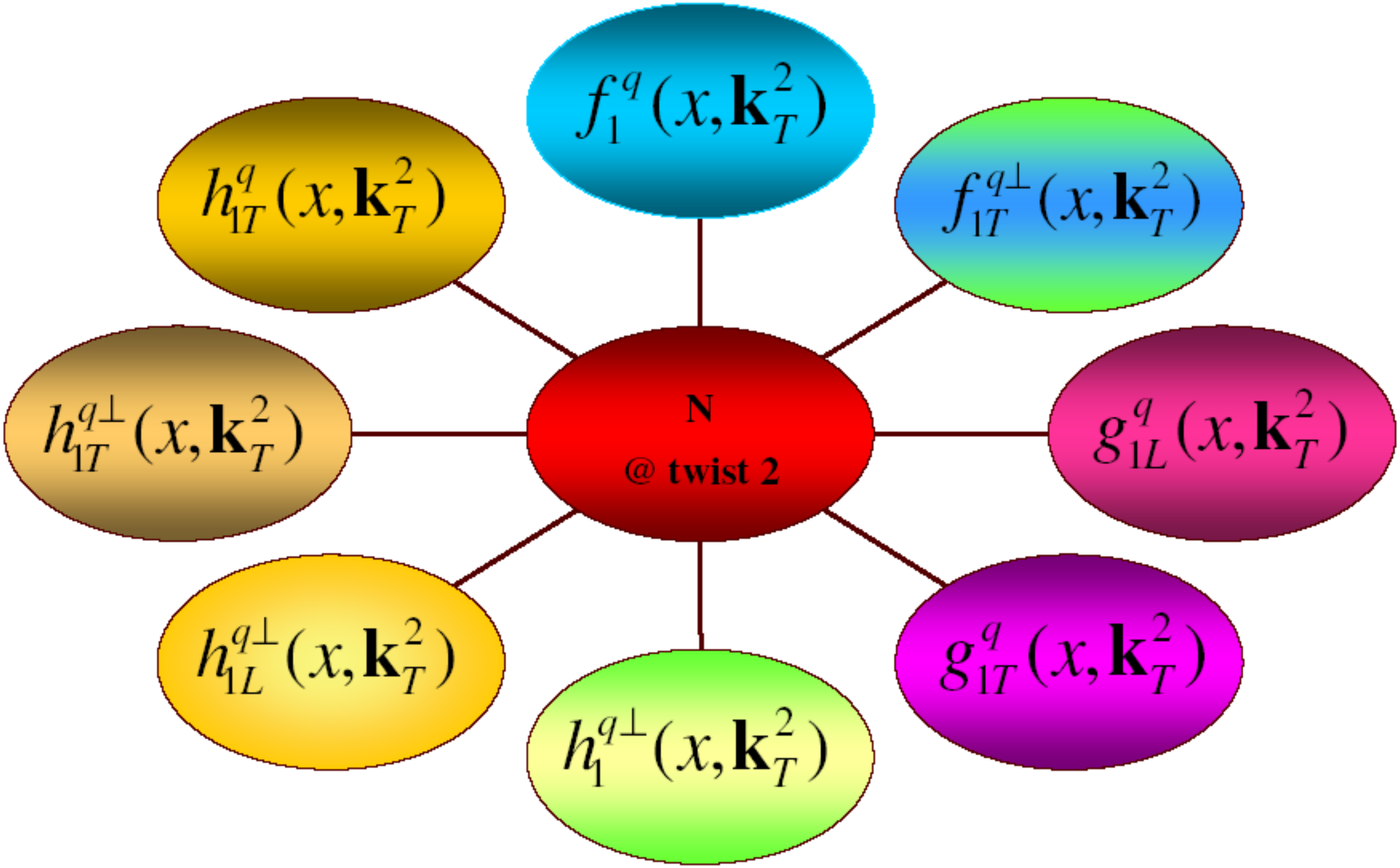
$$\frac{E_C\, d\sigma^{(A,S_A)+(B,S_B)\to C+X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a\, dx_b\, dz}{16\pi^2 x_a x_b z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{k}_{\perp C}\, \delta(\boldsymbol{k}_{\perp C}\cdot\hat{\boldsymbol{p}}_c)\, J(\boldsymbol{k}_{\perp C})$$
$$\times\ \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})\, \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b})$$
$$\times\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\, \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C}$$

$$\rho^{a/A,S_A}_{\lambda_a,\lambda'_a} = \begin{pmatrix} \rho^a_{++} & \rho^a_{+-} \\ \rho^a_{-+} & \rho^a_{--} \end{pmatrix}_{A,S_A} = \frac{1}{2}\begin{pmatrix} 1+P^a_z & P^a_x - iP^a_y \\ P^a_x + iP^a_y & 1-P^a_z \end{pmatrix}_{A,S_A} =$$

$$(P^a_j\, \hat{f}_{a/A,S_Y}) = \Delta\hat{f}^a_{s_j/S_Y} = \hat{f}^a_{s_j/\uparrow} - \hat{f}^a_{-s_j/\uparrow} \equiv \Delta\hat{f}^a_{s_j/\uparrow}(x_a,\boldsymbol{k}_{\perp a})$$
$$(P^a_j\, \hat{f}_{a/A,S_Z}) = \Delta\hat{f}^a_{s_j/S_Z} = \hat{f}^a_{s_j/+} - \hat{f}^a_{-s_j/+} \equiv \Delta\hat{f}^a_{s_j/+}(x_a,\boldsymbol{k}_{\perp a})$$
$$(\hat{f}_{a/A,S_Y}) = \hat{f}_{a/A}(x_a,k_{\perp a}) + \frac{1}{2}\,\Delta\hat{f}_{a/S_Y}(x_a,\boldsymbol{k}_{\perp a})$$

$$
\begin{aligned}
\hat{f}_{a/A,S_T} - \hat{f}_{a/A,-S_T} &= \Delta\hat{f}_{a/S_T}(x_a, \boldsymbol{k}_{\perp a}) = -2\,\frac{k_{\perp a}}{M}\,\sin(\phi_{S_A} - \phi_a)\, f_{1T}^{\perp}(x_a, k_{\perp a}) \\
P^a_x\,\hat{f}_{a/A,S_L} &= \Delta\hat{f}_{s_x/+}(x_a, \boldsymbol{k}_{\perp a}) = \frac{k_{\perp a}}{M}\, h_{1L}^{\perp}(x_a, k_{\perp a}) \\
P^a_y\,\hat{f}_{a/A,S_L} = P^a_y\,\hat{f}_{a/A} &= \Delta\hat{f}_{s_y/A}(x_a, \boldsymbol{k}_{\perp a}) = -\frac{k_{\perp a}}{M}\, h_1^{\perp}(x_a, k_{\perp a}) \\
P^a_z\,\hat{f}_{a/A,S_L} &= \Delta\hat{f}_{s_z/+}(x_a, \boldsymbol{k}_{\perp a}) = g_{1L}(x_a, k_{\perp a}) \\
P^a_z\,\hat{f}_{a/A,S_T} &= \Delta\hat{f}_{s_z/S_T}(x_a, \boldsymbol{k}_{\perp a}) = \frac{k_{\perp a}}{M}\cos(\phi_{S_A} - \phi_a)\, g_{1T}^{\perp}(x_a, k_{\perp a}) \\
P^a_x\,\hat{f}_{a/A,S_T} &= \Delta\hat{f}_{s_x/S_T}(x_a, \boldsymbol{k}_{\perp a}) \\
&= \left[h_{1T}(x_a, k_{\perp a}) + \frac{k_{\perp a}^2}{M^2}\, h_{1T}^{\perp}(x_a, k_{\perp a})\right]\,\cos(\phi_{S_A} - \phi_a) \\
P^a_y\,\hat{f}_{a/A,S_T} &= \Delta\hat{f}_{s_y/S_T}(x_a, \boldsymbol{k}_{\perp a}) \\
&= -\frac{k_{\perp a}}{M}\, h_1^{\perp}(x_a, k_{\perp a}) + h_{1T}(x_a, k_{\perp a})\,\sin(\phi_{S_A} - \phi_a)
\end{aligned}
$$

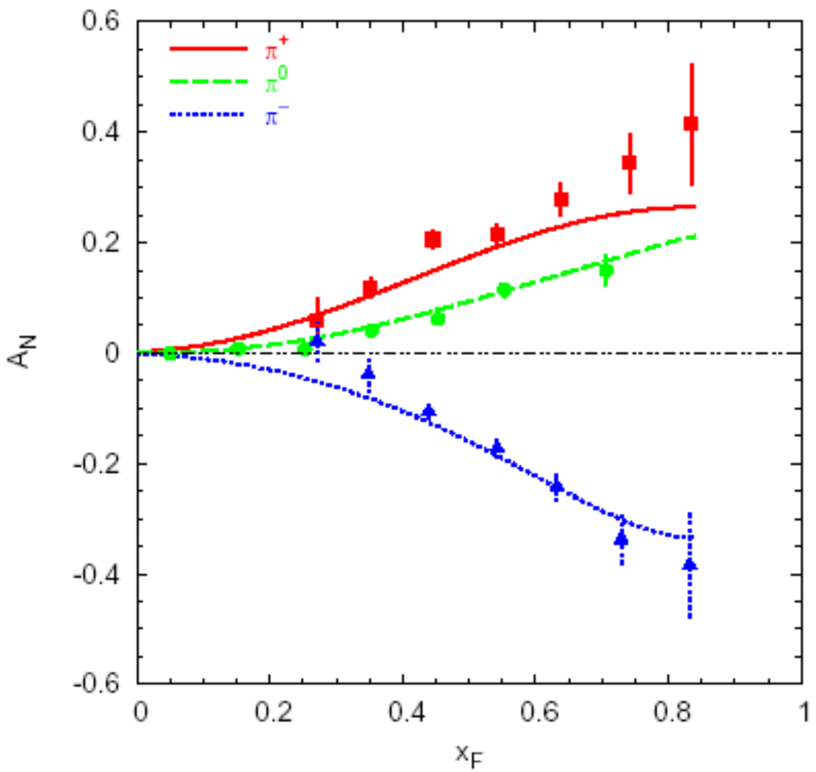
8 leading-twist spin-$k_\perp$ dependent distribution functions



Courtesy of Aram Kotzinian

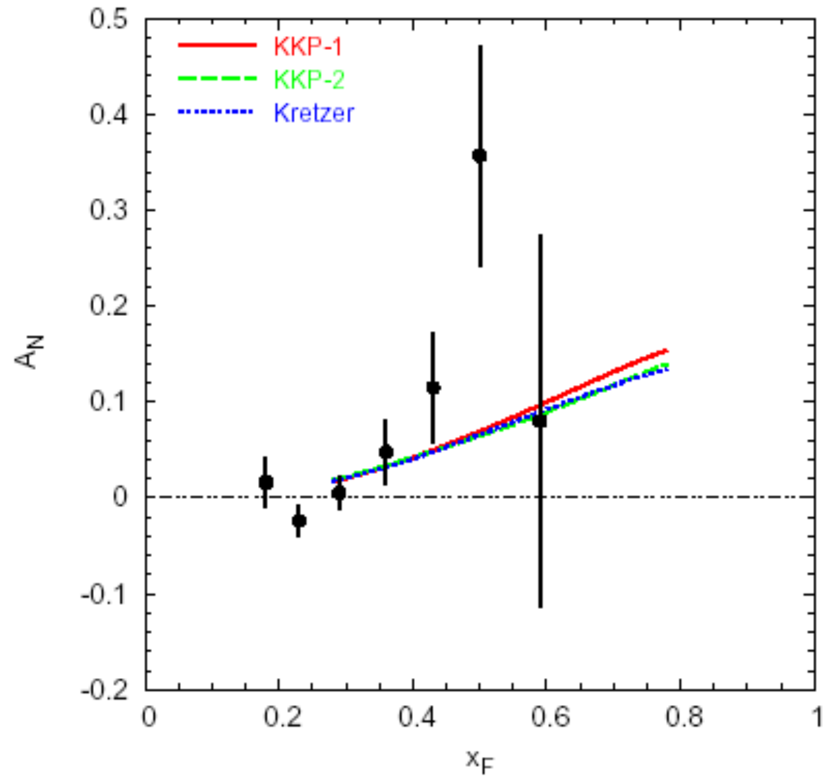
U. D'Alesio, F. Murgia

E704 data



fit

STAR data



prediction

Higher-twist partonic correlations

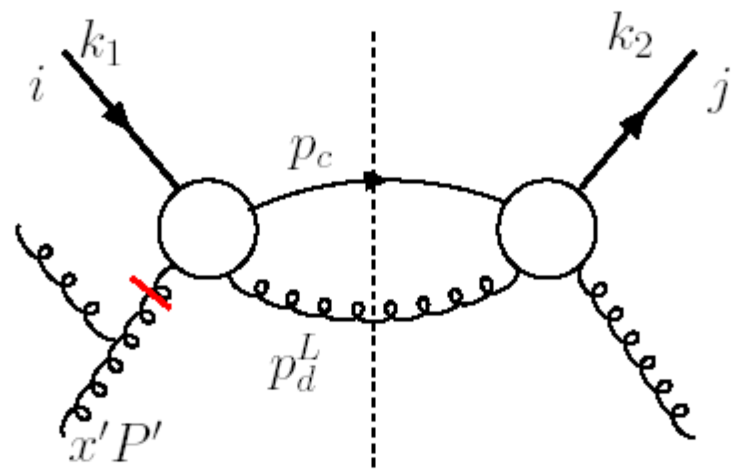
(Efremov, Teryaev; Qiu, Sterman; Kouvaris, Vogelsang, Yuan)

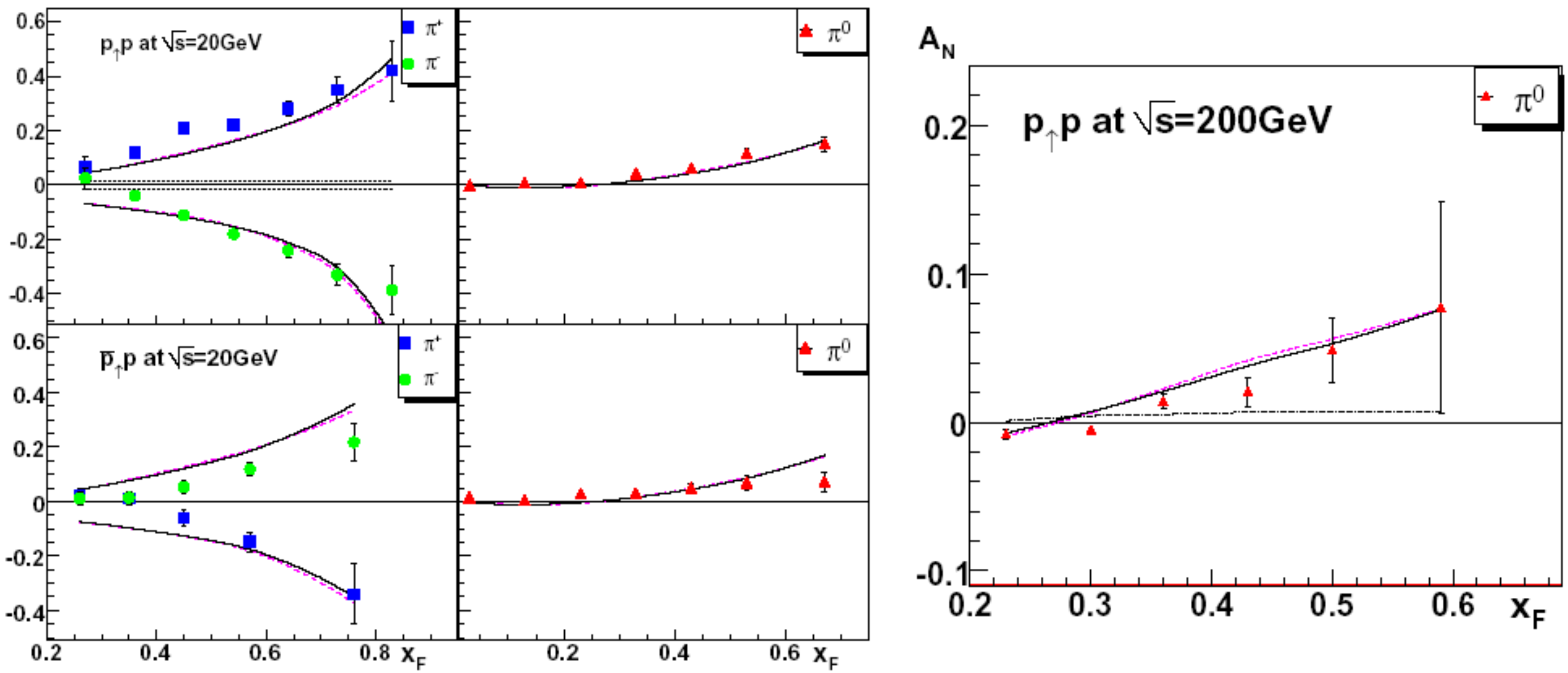
contribution to SSA $(A^{\uparrow} B \rightarrow h\, X)$

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} \underbrace{T_a(k_1, k_2, \boldsymbol{S}_\perp)}_{\text{twist-3 functions}} \otimes f_{b/B}(x_b) \otimes \underbrace{H^{ab\rightarrow c}(k_1, k_2)}_{\text{hard interactions}} \otimes D_{h/c}(z)$$

"collinear expansion" at order $k_{i\perp}$

$$T_a = N_a\, x^{\alpha_a} (1-x)^{\beta_a}\, f_{a/A}(x)$$



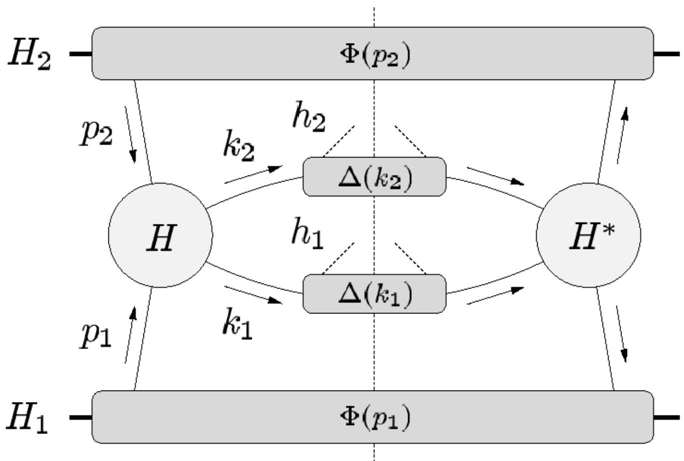


fits of E704 and STAR data

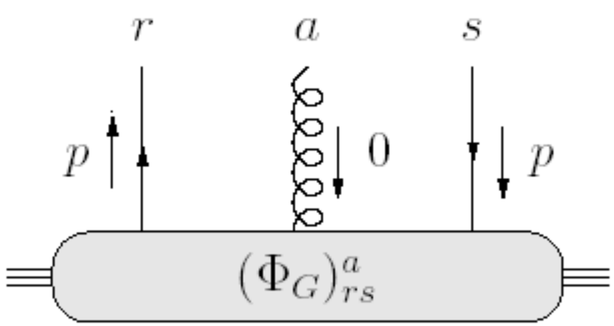
Kouvaris, Qiu, Vogelsang, Yuan

Gluonic pole cross sections and SSA in $H_1 H_2 \to h_1 h_2 X$

Bacchetta, Bomhof, Mulders, Pijlman; Vogelsang, Yuan; Teryaev



factorization ?



Sivers contribution to SSA $(T_a \propto f_{1T}^{\perp(1)})$

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} f_{1T}^{\perp(1)}(x_1) \otimes f_{b/H_2}(x_2) \otimes \mathrm{d}\hat{\sigma}_{[a]b\to cd} \otimes D_{h_1/c}(z_1)\, D_{h_2/d}(z_2)$$

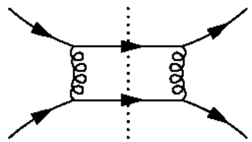
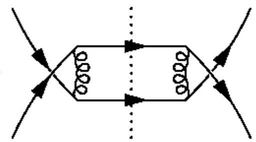
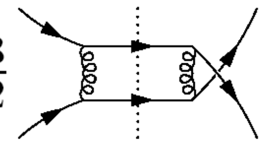
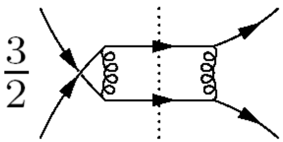
gluonic pole cross sections take into account gauge links

$$\mathrm{d}\hat{\sigma}_{[a]b\to cd} = \sum_D C_G^{[D]}\, \mathrm{d}\hat{\sigma}^D_{ab\to cd}$$

$C_G^{[D]}$ Diagram dependent Gauge link Colour factors

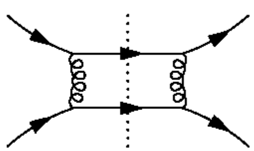
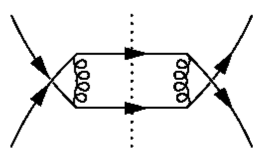
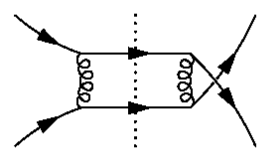
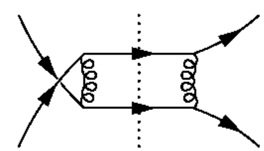
(breaking of factorization?)

Gluonic pole cross sections and SSA in $H_1 H_2 \to h_1 h_2 X$

$\frac{d\hat{\sigma}_{[q]q\to qq}}{d\hat{t}} = \frac{1}{2}$  $+\ \frac{1}{2}$  $+\ \frac{3}{2}$  $+\ \frac{3}{2}$ 

$$= \frac{4\pi\alpha_S^2}{9\hat{s}^2}\left\{ \frac{\hat{s}^2+\hat{u}^2}{2\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{2\hat{u}^2} + \frac{\hat{s}^2}{\hat{t}\hat{u}} \right\}$$

to be compared with the usual cross section

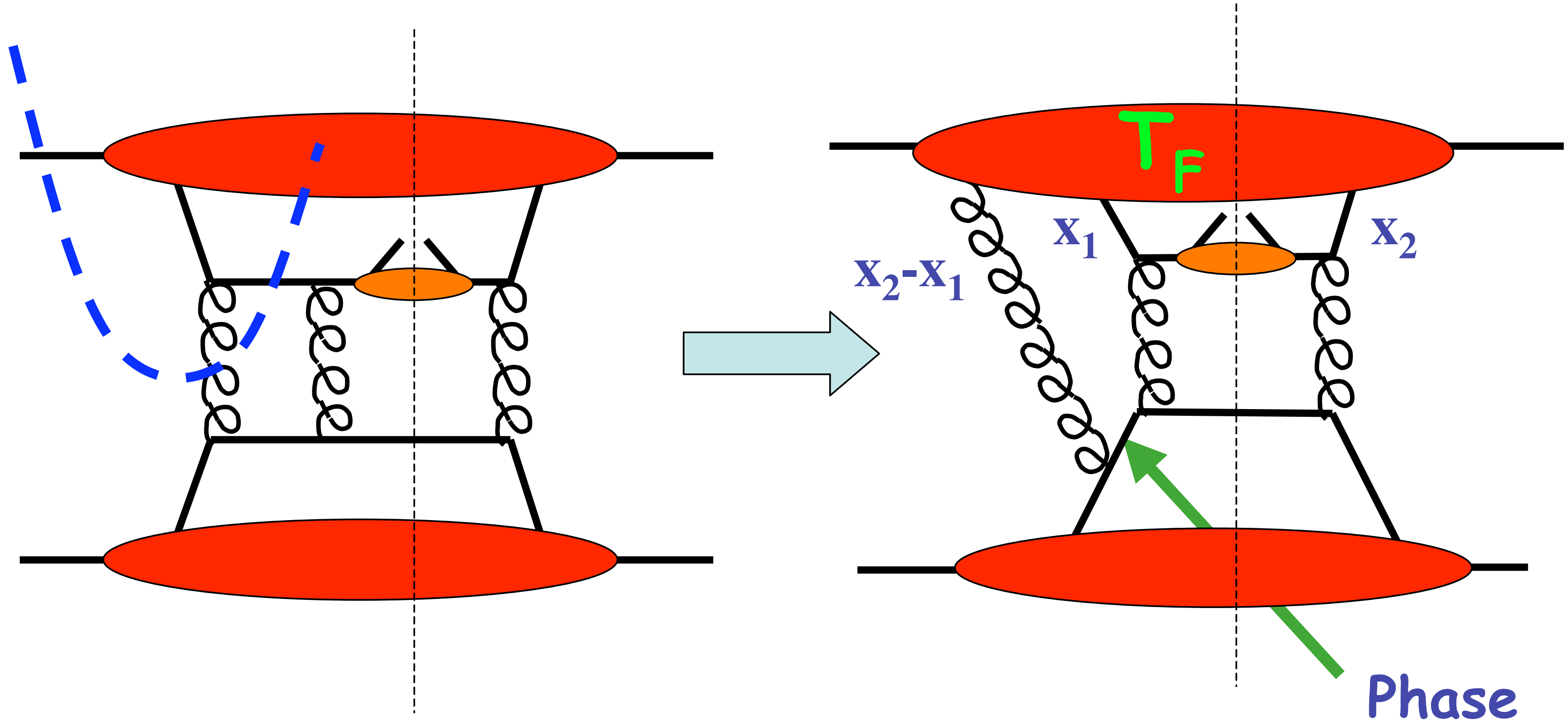
$\frac{d\hat{\sigma}_{qq\to qq}}{d\hat{t}} =$  $+$  $-$  $-$ 

$$= \frac{4\pi\alpha_S^2}{9\hat{s}^2}\left\{ \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2} - \frac{2}{3}\frac{\hat{s}^2}{\hat{t}\hat{u}} \right\}$$

$$\mathrm{d}\hat{\sigma}_{[\ell]q\to\ell q} = \mathrm{d}\hat{\sigma}_{\ell q\to\ell q} \qquad\qquad \mathrm{d}\hat{\sigma}_{[q]\bar{q}\to\ell^+\ell^-} = -\mathrm{d}\hat{\sigma}_{q\bar{q}\to\ell^+\ell^-}$$

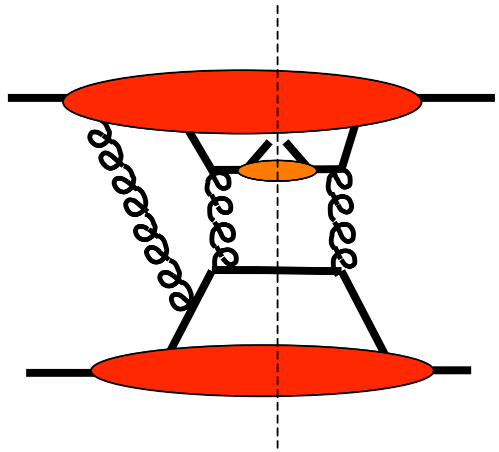
From W. Vogelsang talk at Beijing 2008

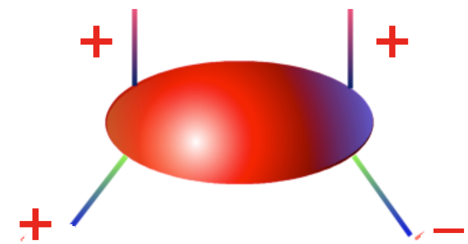
- **power-suppressed effects in QCD much richer than mass terms** (Efremov, Teryaev; Qiu, Sterman; Eguchi, Koike, Tanaka)



Collinear factorization in terms of "quark-gluon correlation":

$$T_F(x,x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+y_1^-} \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \left[\int dy_2^- \epsilon^{s_T \sigma n \bar{n}} F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$





- phase in hard scattering
- hel. flip because of $qg\bar{q}$
- factorization for $pp \to \pi X$ established
- phenomenology

Qiu, Sterman
Kouvaris, Qiu, WV, Yuan

- phase in distribution fct. (but where exactly?)
- hel. flip because of OAM
- factorization for $pp \to \pi X$ *assumed*
- phenomenology

Anselmino, Boglione,
D'Alesio, Leader, Melis, Murgia, ...

Crucial role of gauge-links in TMDs

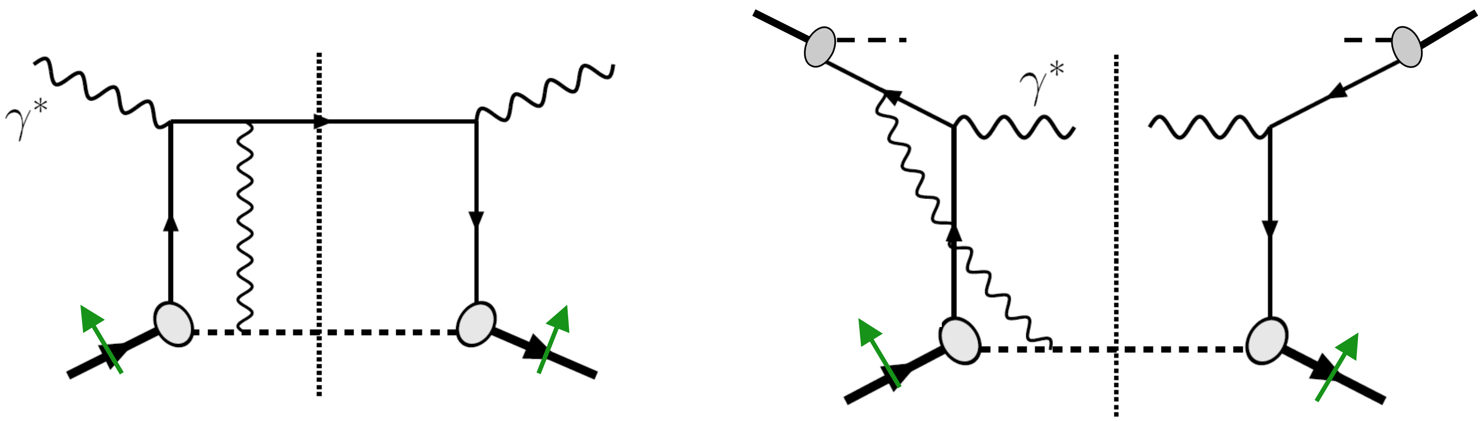
Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan;

- profound implication:

process-dependece of Sivers functions

$$f_{\mathrm{DY}}^{\mathrm{Sivers}}(x, k_\perp) = - f_{\mathrm{DIS}}^{\mathrm{Sivers}}(x, k_\perp)$$

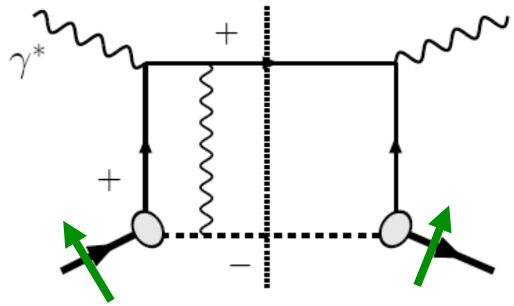
DIS: "attractive" **DY:** "repulsive"

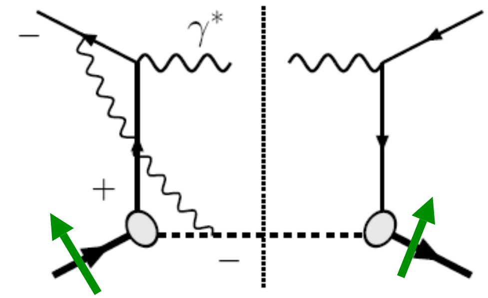


- hugely important in QCD -- tests a lot of what we know about description of hard processes

Non-universality of Sivers Asymmetries: Unique Prediction of Gauge Theory !

Simple QED example:

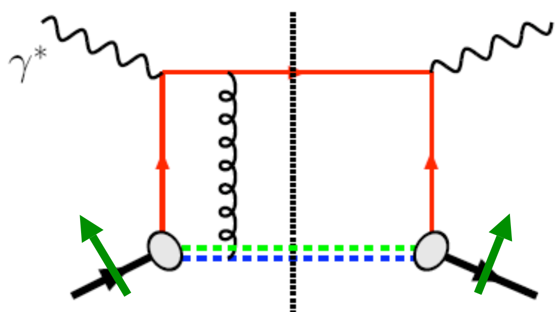


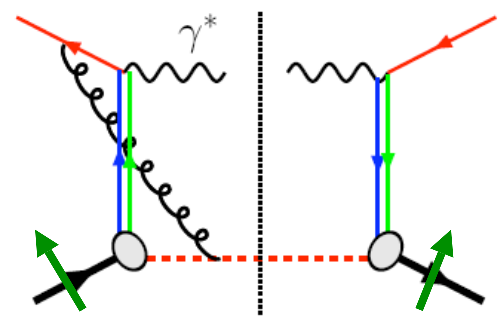


DIS: attractive

Drell-Yan: repulsive

Same in QCD:

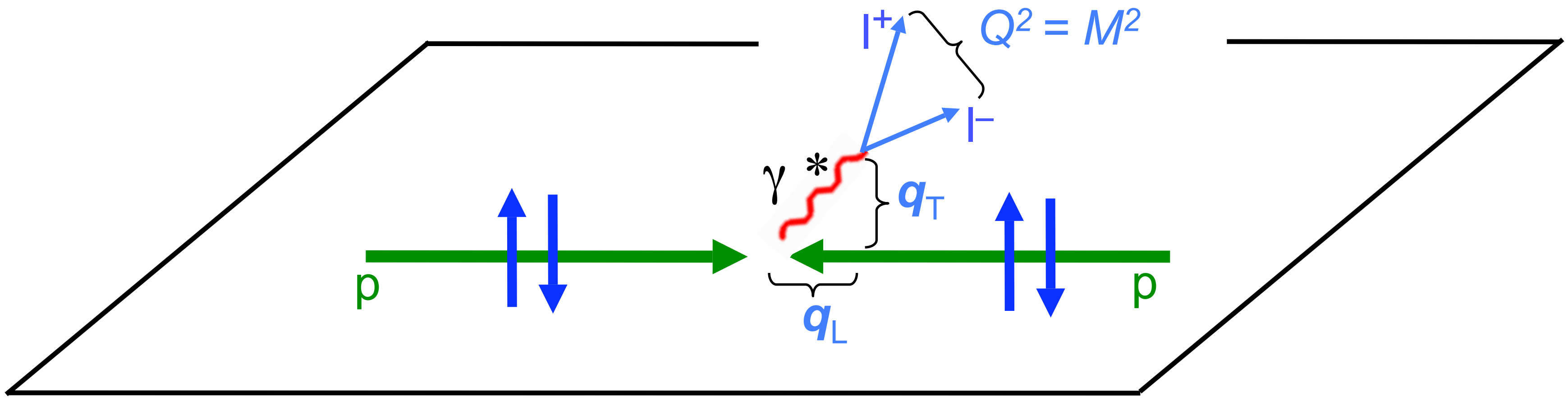




As a result:

$$\boxed{\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}}$$

TMDs and SSAs in Drell-Yan processes



factorization holds, two scales, M^2, and q_T

$$d\sigma^{D-Y} = \sum_a f_q(x_1, \boldsymbol{k}_{\perp 1}; Q^2) \otimes f_{\bar{q}}(x_2, \boldsymbol{k}_{\perp 2}; Q^2)\, d\hat{\sigma}^{q\bar{q}\to \ell^+\ell^-}$$

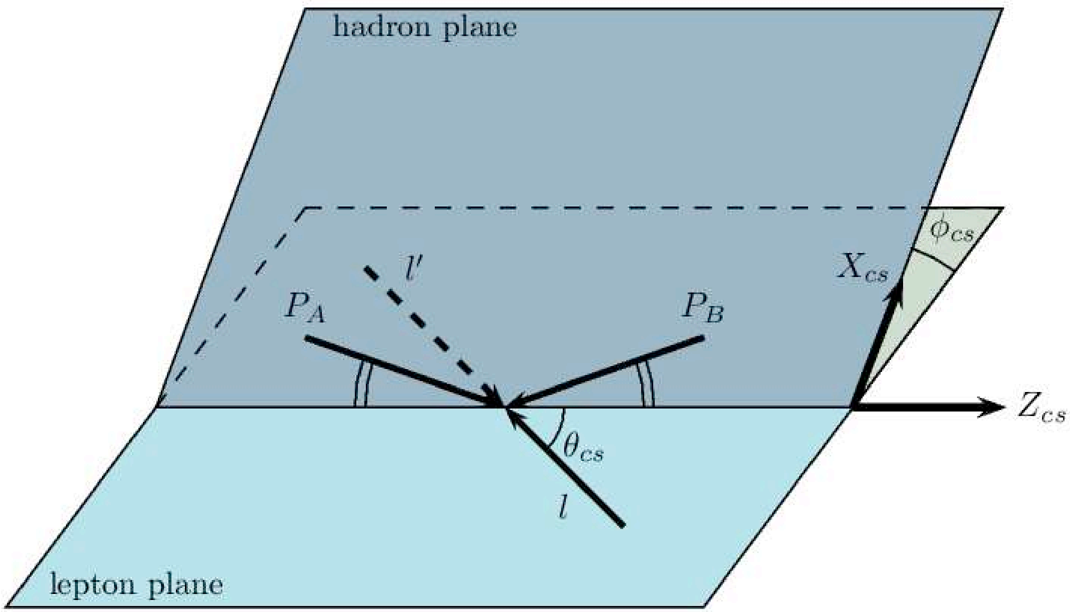
3 planes: plane $\perp$ to polarization vectors,

$p - \gamma^*$ plane, $l^+ - l^-$ plane

no fragmentation process

Unpolarized cross section already very interesting

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\,\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

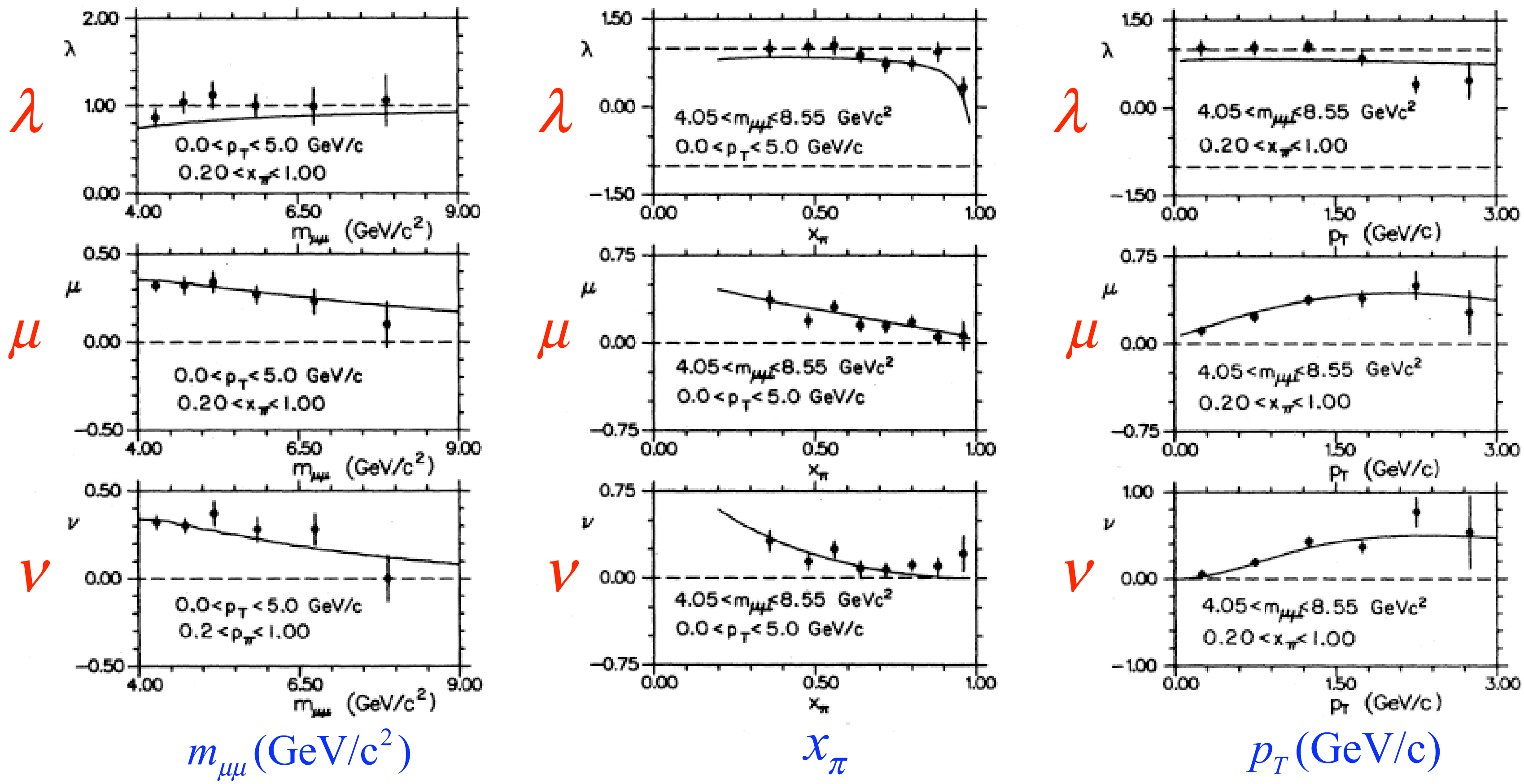


Collins-Soper frame

naive collinear parton model: $\lambda = 1 \quad \mu = \nu = 0$

Decay angular distributions in pion-induced Drell-Yan

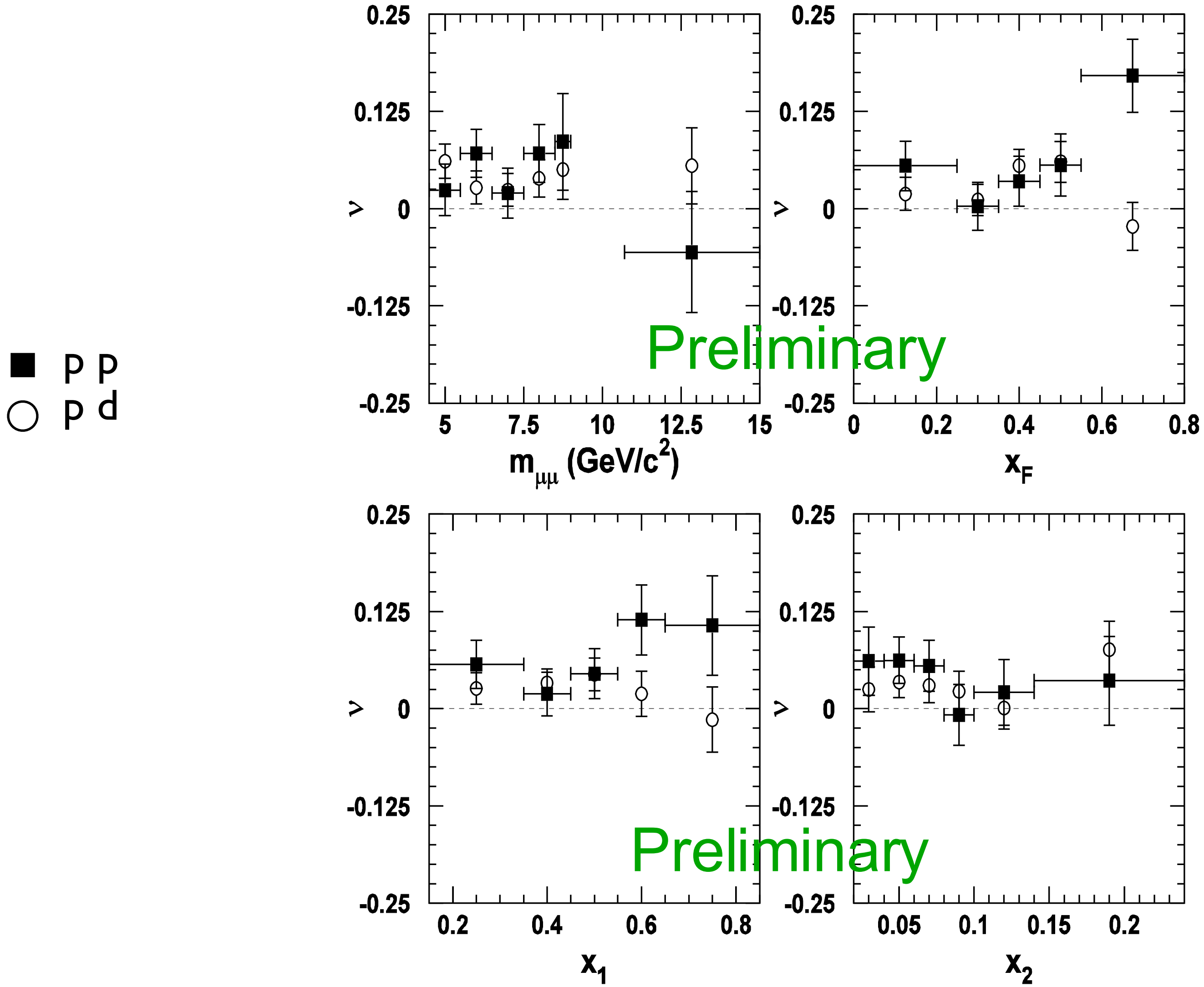
E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92



$$\lambda \neq 1 \quad \mu, \nu \neq 0 \quad 1 - \lambda - 2\nu \neq 0$$

(Jen-Chieh Peng talk at transversity 2008, Ferrara)

Angular Distribution in E866 p+p/p+d Drell-Yan



PRL 99 (2007) 082301

TMDs help: for example, the $\cos 2\phi$ term can be originated by the Boer-Mulders effect

$$d\sigma \propto \underbrace{d\sigma^0}_{1+\cos^2\theta} + \sum_q h_{1q}^{\perp}(x_1, k_\perp) \otimes h_{1\bar{q}}^{\perp}(x_2, k_\perp) \otimes \underbrace{(d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow})}_{\sin^2\theta\cos 2\phi}$$

Polarized D-Y processes with intrinsic $k_\perp$ have a rich structure, similar to SIDIS

SSA in D-Y has a contribution from the coupling of the transversity distribution to B-M function

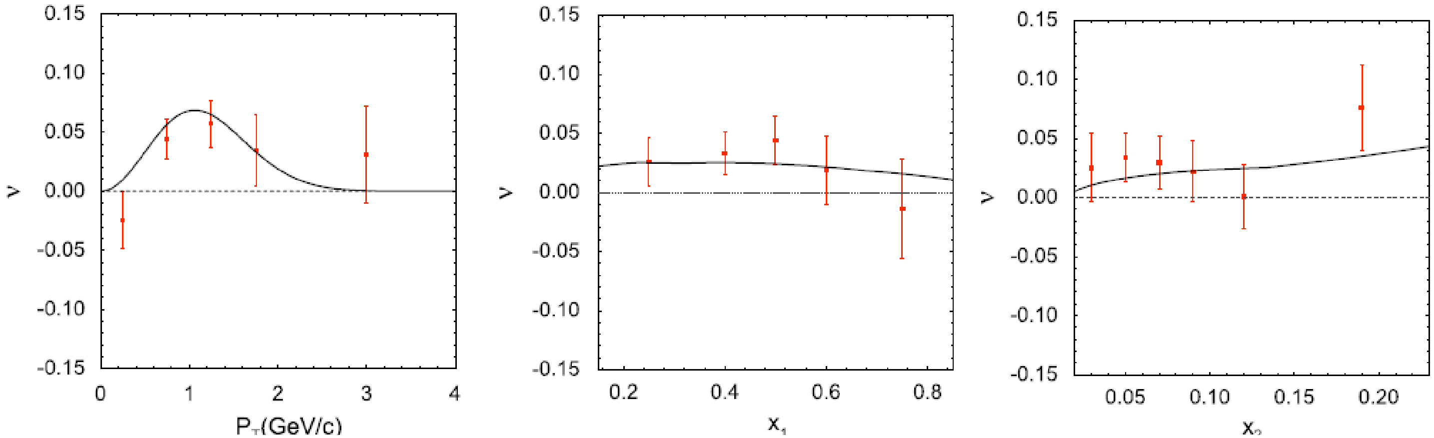
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto \sum_q h_{1q}(x_1) \otimes h_{1\bar{q}}^{\perp}(x_2, k_\perp) \otimes \underbrace{(d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow})}_{\cos 2\phi}$$

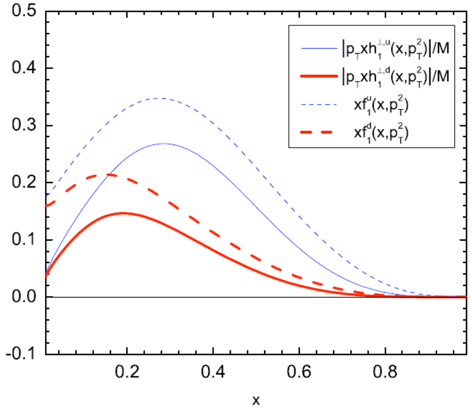
B-M $\quad f_{q,\boldsymbol{s}_q/p}(x, \boldsymbol{k}_\perp) = \frac{1}{2} f_{q/p}(x, k_\perp) - \frac{k_\perp}{2M} h_{1q}^{\perp}(x, k_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv:0803.1692)

Fit to the p+d Drell-Yan data





Satisfy the positivity bound

Sivers effect in D-Y processes

By looking at the $d^4\sigma/d^4q$ cross section one can single out the Sivers effect in D-Y processes

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto \sum_q \Delta^N f_{q/p}(x_1, k_\perp) \otimes f_{\bar{q}/p}(x_2) \otimes \mathrm{d}\hat{\sigma}$$

$$A_N = \frac{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow}{\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow}$$

$$\frac{\sum_q e_q^2 \int d^2\boldsymbol{k}_{\perp q}\, d^2\boldsymbol{k}_{\perp\bar{q}}\, \delta^2(\boldsymbol{k}_{\perp q} + \boldsymbol{k}_{\perp\bar{q}} - \boldsymbol{q}_T)\, \Delta^N f_{q/p^\uparrow}(x_q, \boldsymbol{k}_\perp)\, f_{\bar{q}/p^\uparrow}(x_{\bar{q}}, \boldsymbol{k}_{\perp\bar{q}})}{2\sum_q e_q^2 \int d^2\boldsymbol{k}_{\perp q}\, d^2\boldsymbol{k}_{\perp\bar{q}}\, \delta^2(\boldsymbol{k}_{\perp q} + \boldsymbol{k}_{\perp\bar{q}} - \boldsymbol{q}_T)\, f_{q/p^\uparrow}(x_q, \boldsymbol{k}_\perp)\, f_{\bar{q}/p^\uparrow}(x_{\bar{q}}, \boldsymbol{k}_{\perp\bar{q}})}$$

$$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$$

$$A_N^{\sin(\phi_S - \phi_\gamma)} \equiv \frac{2\int_0^{2\pi} \mathrm{d}\phi_\gamma\, [\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow]\, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} \mathrm{d}\phi_\gamma\, [\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$

(p-p c.m. frame)

Predictions for A_N at RHIC (S. Melis)

Sivers functions as extracted by

M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin and C. Türk

from SIDIS data, **with opposite sign**

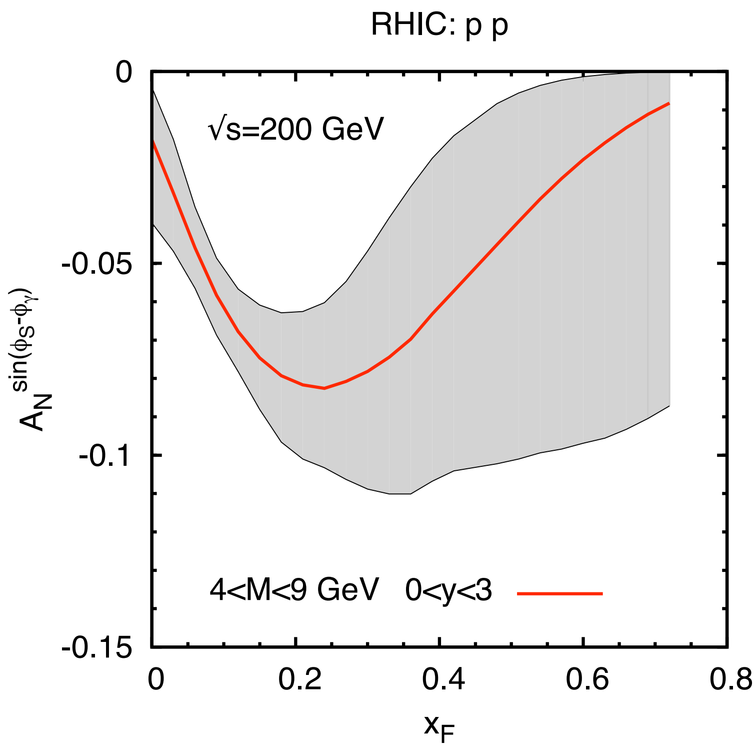


Figure 9: The single spin asymmetries $A_N^{\sin(\phi_S-\phi_\gamma)}$ for the Drell-Yan process $p^{\uparrow}p \rightarrow \mu^+\mu - + X$ at RHIC, as function of $x_F = x_a - x_b$, averaged over the invariant mass range $4 < M < 9$, rapidity $0 < y < 3$ and transverse momentum $0 < q_T < 1$ GeV/c, for $\sqrt{s} = 200$ GeV.

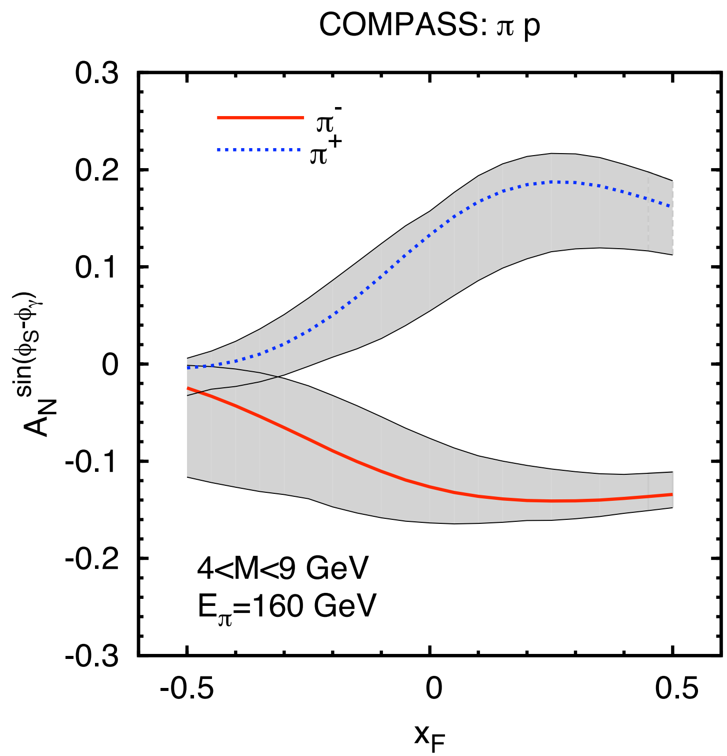


Figure 1: The single spin asymmetries $A_N^{\sin(\phi_S-\phi_\gamma)}$ for the Drell-Yan process $\pi p \to \mu^+\mu- + X$ at COMPASS, as function of $x_F = x_a - x_b$, averaged over the invariant mass range $4 < M < 9$ and transverse momentum $0 < q_T < 1$ GeV/c, for a pion beam energy of 160 GeV/c.

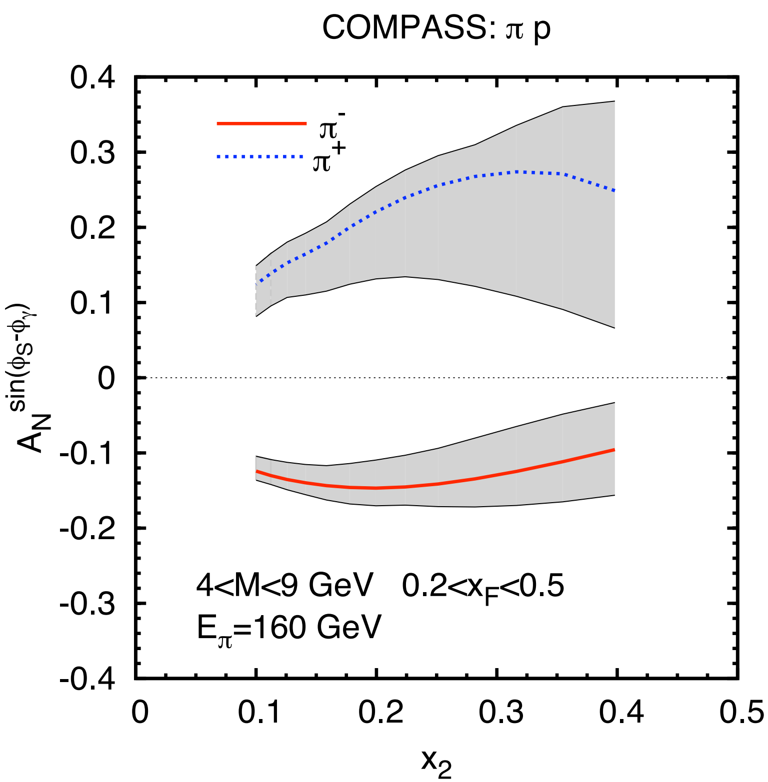


Figure 2: The single spin asymmetries $A_N^{\sin(\phi_S-\phi_\gamma)}$ for the Drell-Yan process $\pi p \to \mu^+\mu- + X$ at COMPASS, as function of x_b, averaged over the invariant mass range $4 < M < 9$, $0.2 < x_F < 0.5$ and transverse momentum $0 < q_T < 1$ GeV/c, for a pion beam energy of 160 GeV/c. MRSS92 pion pdf

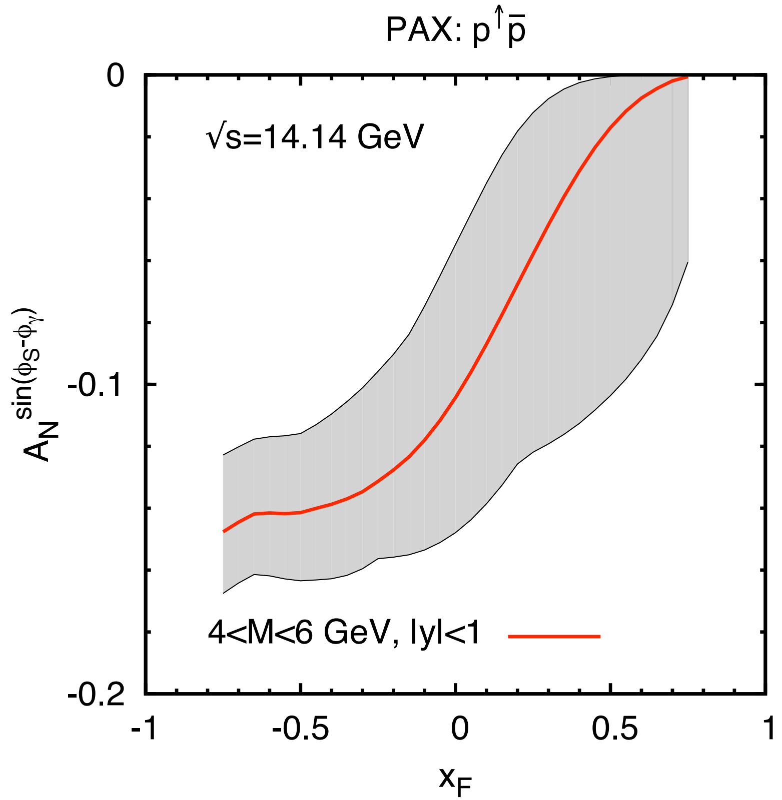
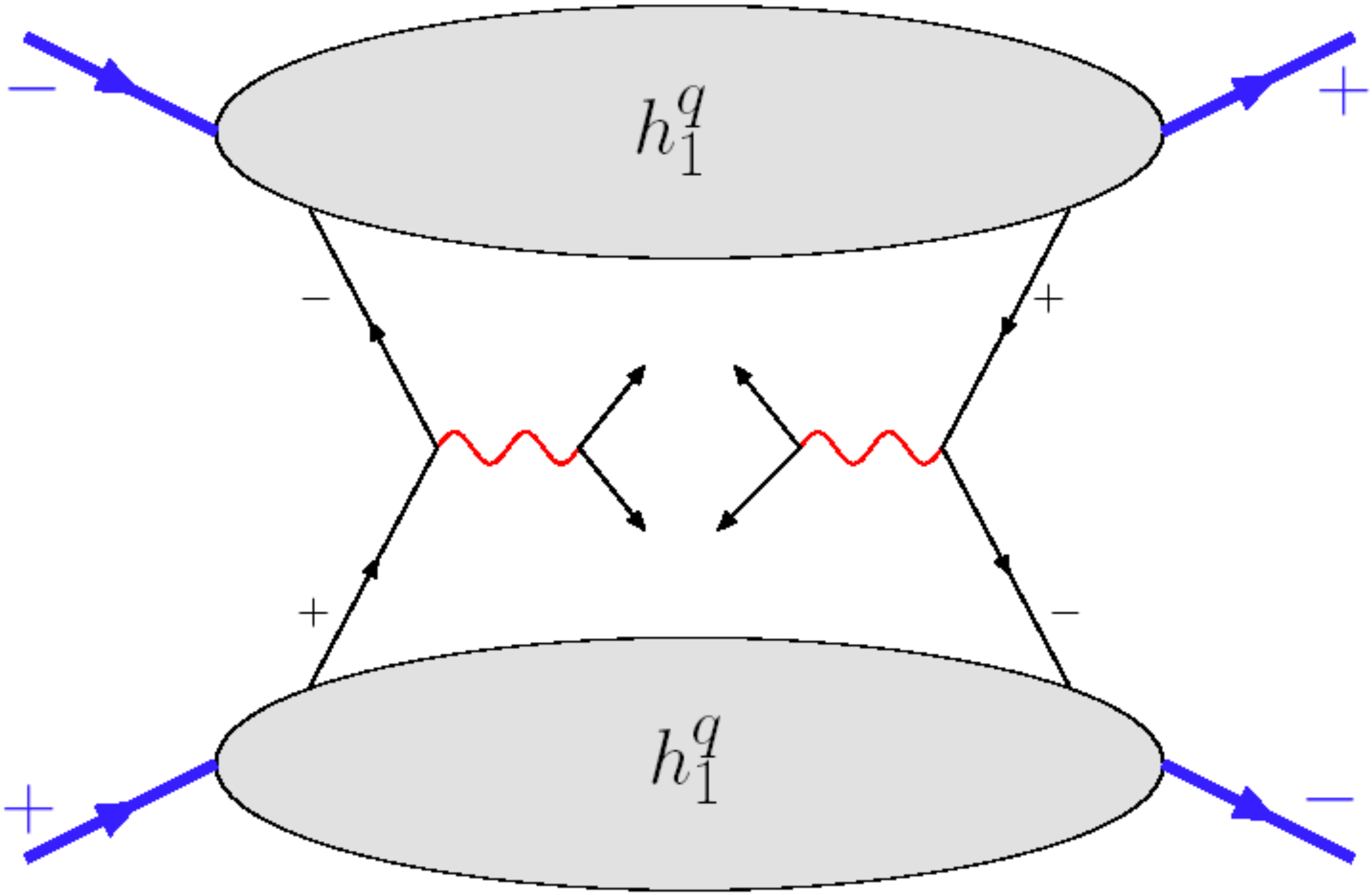


Figure 6: The single spin asymmetries $A_N^{\sin(\phi_S-\phi_\gamma)}$ for the Drell-Yan process $p^{\uparrow}\bar{p} \to \mu^+\mu - + X$ at PAX, as function of $x_F = x_a - x_b$, averaged over the invariant mass range $4 < M < 6$, rapidity $|y| < 1$ and transverse momentum $0 < q_T < 1$ GeV/c, for $\sqrt{s} = 14$ GeV.

Possible direct access to transversity: Drell-Yan processes

$$p\,p \to \ell^+\ell^-,\ \pi\,p \to \ell^+\ell^-,\ p\,\bar{p} \to \ell^+\ell^-$$

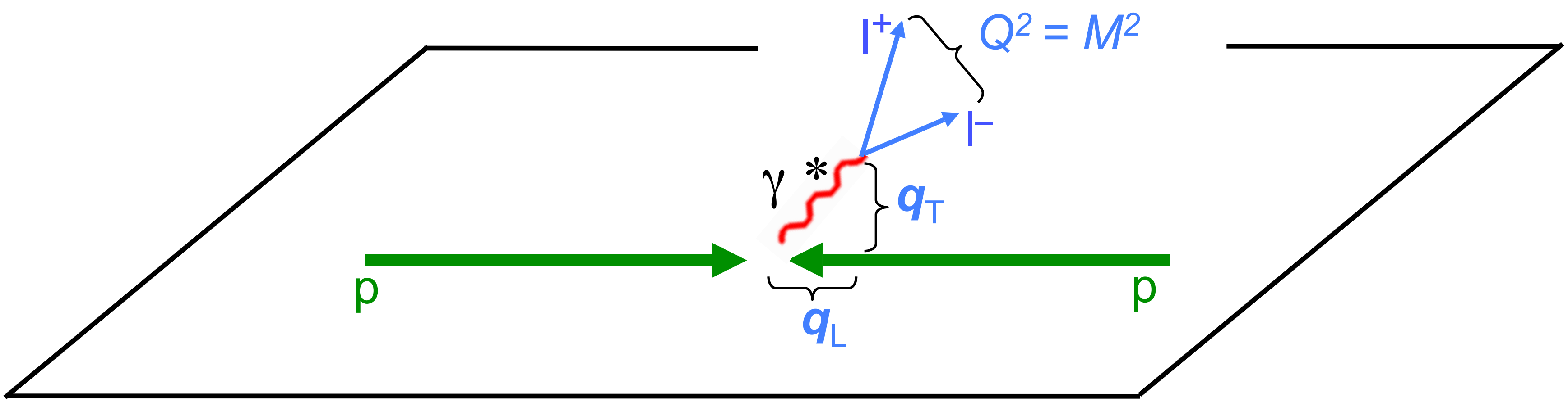


Simple partonic cross section at collinear level

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M^2\,\mathrm{d}x_F} = \frac{4\pi\alpha^2}{9M^2 s}\,\frac{1}{x_1+x_2}\sum_q e_q^2\left[q(x_1,Q^2)\,\bar{q}(x_2,Q^2)+\bar{q}(x_1,Q^2)\,q(x_2,Q^2)\right]$$

$$x_F = x_1 - x_2 \qquad x_1\,x_2 = M^2/s \equiv \tau \qquad x_F = 2q_L/\sqrt{s}$$

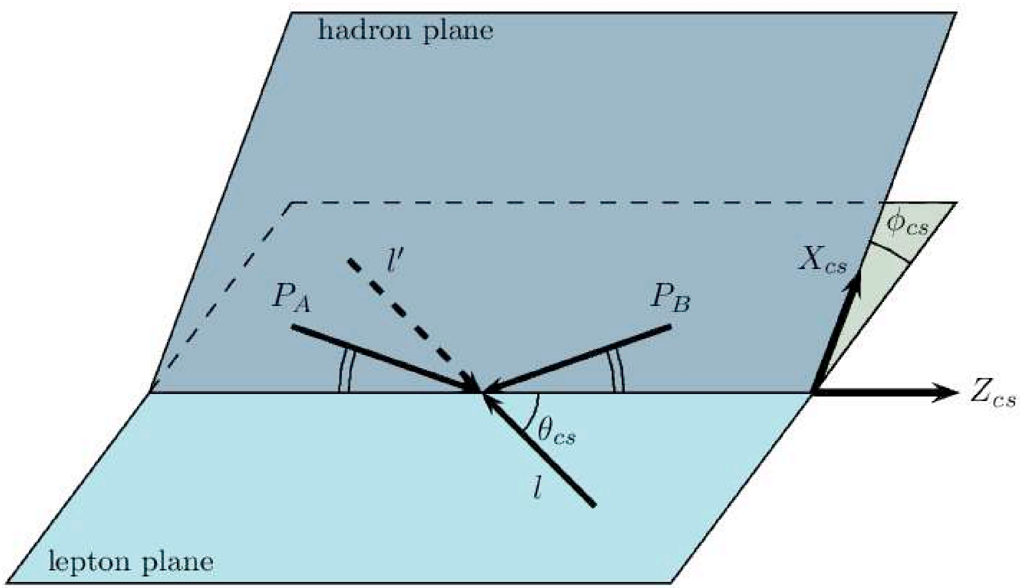
range of x_1, x_2 explored depends on τ



Direct access to transversity from double transverse spin asymmetry

$$A_{TT} = \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} + \mathrm{d}\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_{1q}(x_1)\, h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1)\, h_{1q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_1)\, \bar{q}(x_2) + \bar{q}(x_1)\, q(x_2)\right]}$$

$$\hat{a}_{TT} = \frac{\mathrm{d}\hat{\sigma}^{\uparrow\uparrow} - \mathrm{d}\hat{\sigma}^{\uparrow\downarrow}}{\mathrm{d}\hat{\sigma}^{\uparrow\uparrow} + \mathrm{d}\hat{\sigma}^{\uparrow\downarrow}} = \frac{\sin^2\theta}{1 + \cos^2\theta}\, \cos(2\phi)$$



RHIC energies: $\sqrt{s} = 200\,\mathrm{GeV}$ $\quad M^2 \leq 100\,\mathrm{GeV}$

$\Rightarrow$ $\tau \leq 2 \cdot 10^{-3}$ small x_1 and/or x_2

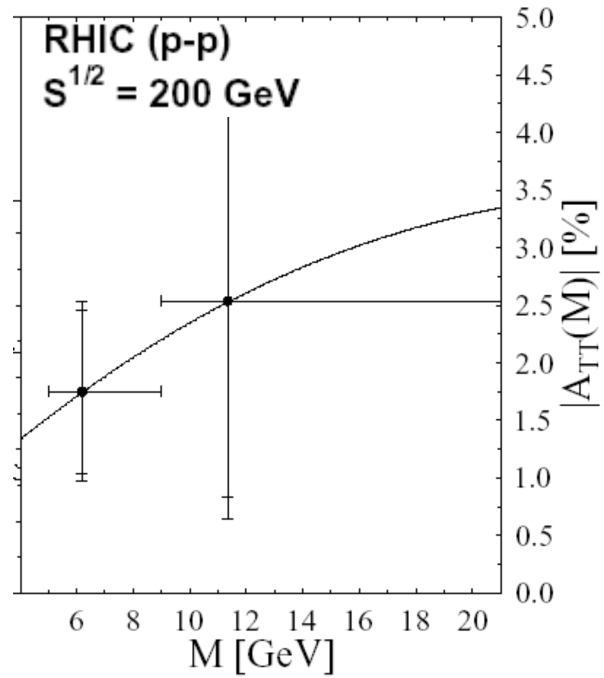
$h_{1q}(x, Q^2)$ evolution much slower than $\Delta q(x, Q^2)$ and $q(x, Q^2)$ at small x

$\Rightarrow$ A_{TT} at RHIC is very small
smaller s would help

Barone, Calarco, Drago
Martin, Schäfer, Stratmann, Vogelsang

A_{TT} for Drell-Yan processes at RHIC

upgrades in luminosity expected

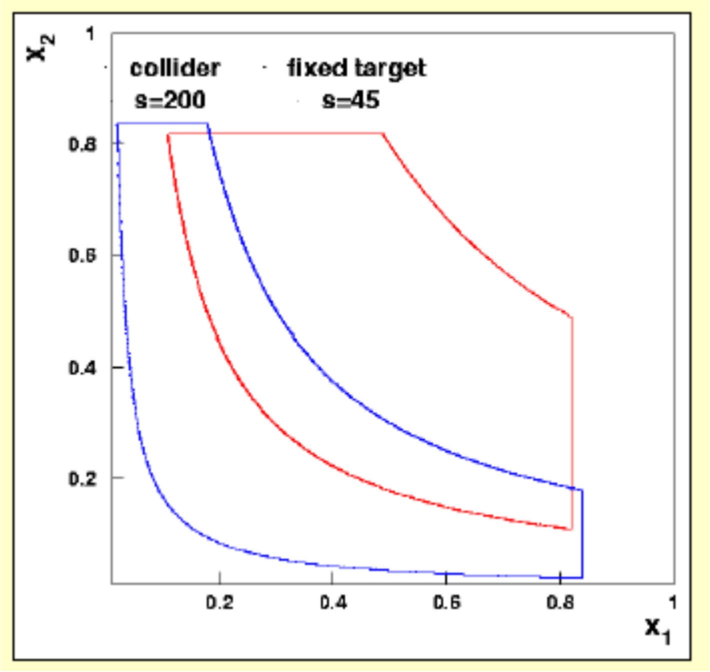


h_1 from $p^\uparrow \bar{p}^\uparrow \to \ell^+ \ell^- X$ at GSI

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \, [h_{1q}(x_1)\, h_{1q}(x_2) + h_{1\bar{q}}(x_1)\, h_{1\bar{q}}(x_2)]}{\sum_q e_q^2 \, [q(x_1)\, q(x_2) + \bar{q}(x_1)\, \bar{q}(x_2)]} \simeq \hat{a}_{TT} \frac{h_{1u}(x_1)\, h_{1u}(x_2)}{u(x_1)\, u(x_2)}$$

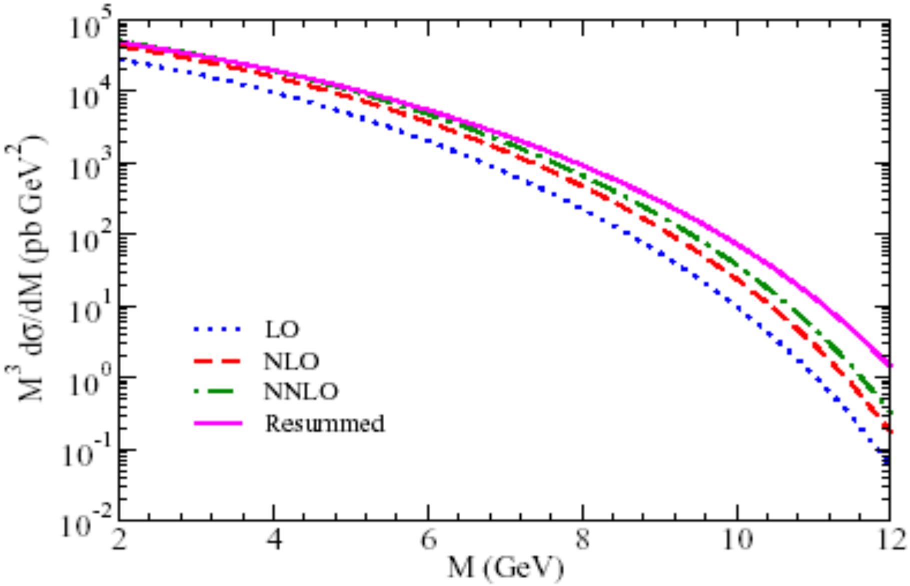
large x_1, x_2

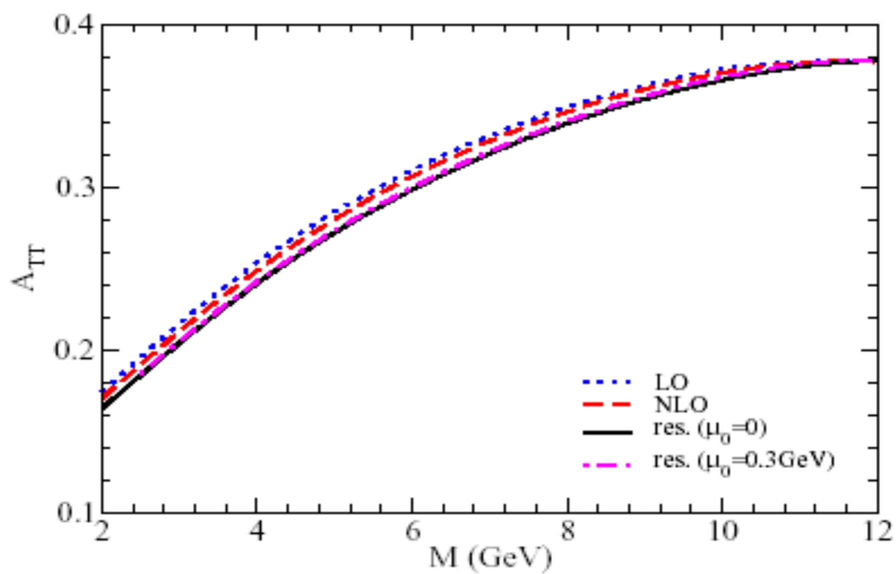
GSI energies: $s = 30 - 210 \,\mathrm{GeV}^2$ $\quad M^2 \geq 2 \,\mathrm{GeV}^2$



one measures h_1 in the quark valence region: A_{TT} is estimated to be large, between 0.2 and 0.4

PAX proposal: hep-ex/0505054





results for A_{TT} stable under QCD corrections

H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya

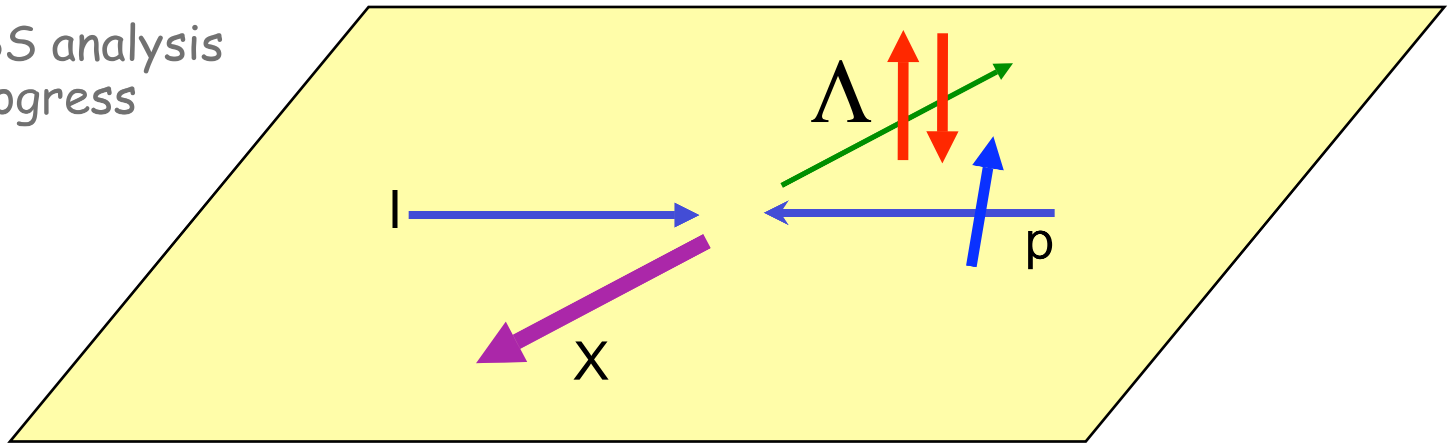
M. Guzzi, V. Barone, A. Cafarella, C. Corianò and P.G. Ratcliffe

Some alternative accesses to transversity

Inclusive Λ production and measure of Λ polarization

need to know transverse fragmentation function $\Delta_T D = D_{q^\uparrow}^{\Lambda^\uparrow} - D_{q^\uparrow}^{\Lambda^\downarrow}$

COMPASS analysis in progress



the Λ polarization vector measured from the proton angular distribution in the $\Lambda \to \pi$p decay in the Λ helicity rest frame

$$
\begin{aligned}
W(\theta_p, \phi_p) &= \frac{1}{4\pi}\left[1 + \alpha(P_z \cos\theta_p + P_x \sin\theta_p \cos\phi_p + P_y \sin\theta_p \sin\phi_p)\right] \\
&= \frac{1}{4\pi}[1 + \boldsymbol{P} \cdot \hat{\boldsymbol{p}}]
\end{aligned}
$$

$\alpha = 0.642 \pm 0.013$

collinear configuration,
no need for intrinsic $\boldsymbol{k}_\perp$

$$P_N^{[0S_N]} = \frac{2(1-y)}{1+(1-y)^2} \, \frac{\sum_q e_q^2 \, h_{1q}(x) \, \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 \, q(x) \, D_{\Lambda/q}(z)}$$

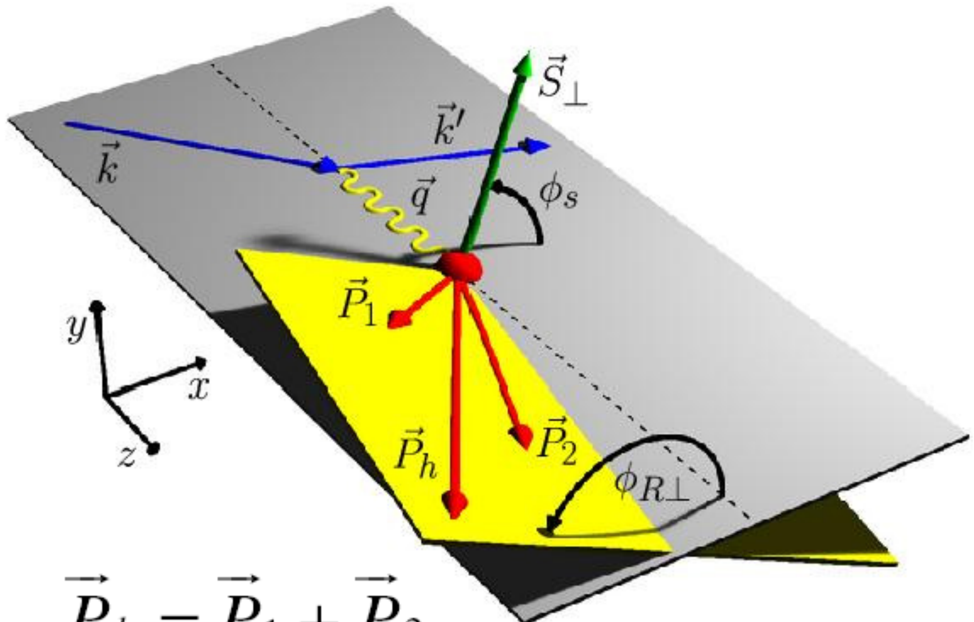
$$\Delta_T D = D_{q^\uparrow}^{\Lambda^\uparrow} - D_{q^\uparrow}^{\Lambda^\downarrow}$$

$$P_N^{[0S_N]} \simeq \frac{2(1-y)}{1+(1-y)^2} \, \frac{4h_{1u}+h_{1d}}{4u+d} \, \frac{\Delta_T D_{\Lambda/u}}{D_{\Lambda/u}}$$

similar result in $p \, p^\uparrow \to \Lambda^\uparrow X$

$$P_N(\Lambda) \sim \sum_{abc} f_{a/p} \otimes h_{1b} \otimes \mathrm{d}\Delta\sigma^{ab\to c\cdots} \otimes \Delta_T D_{\Lambda/c}$$

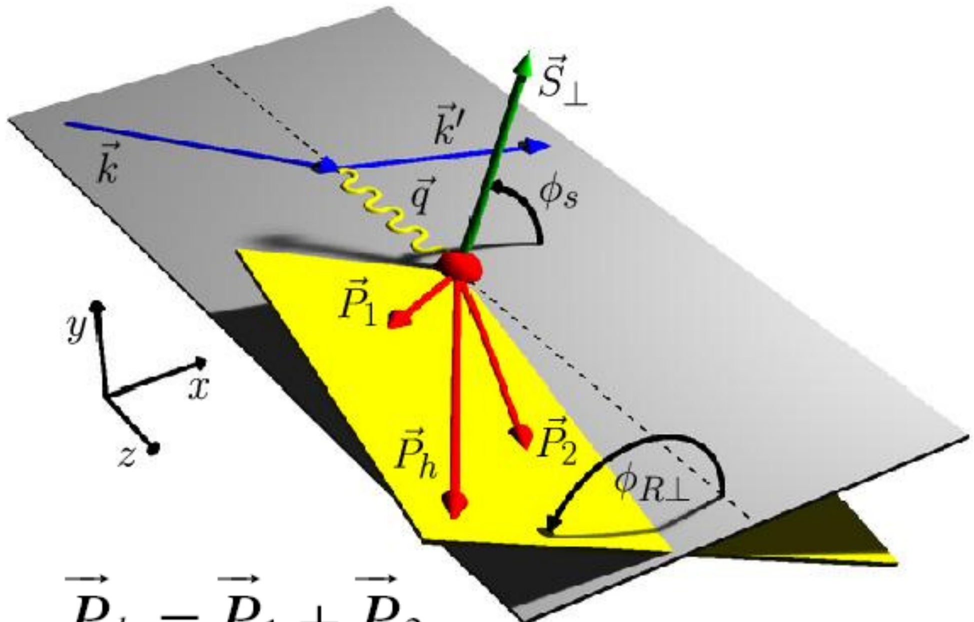
Two hadron production in SIDIS
Di-hadron Fragmentation Function (DiFF)



$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

Chiral odd fragmentation function of a transversely polarized quark into two hadrons (interference between s and p wave)

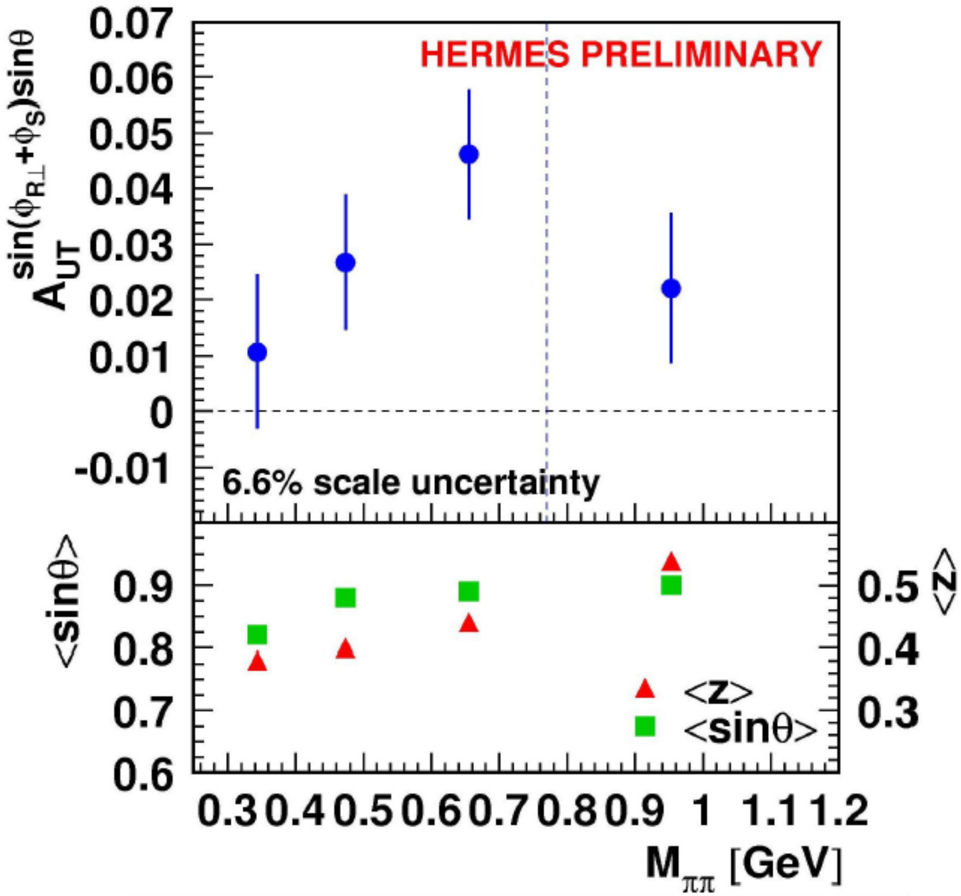
Two hadron production in SIDIS
Di-hadron Fragmentation Function (DiFF)



$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

Chiral odd fragmentation function of a transversely polarized quark into two hadrons (interference between s and p wave)

Bacchetta, Boer, Jaffe, Jakob, Radici ...



$$A_{UT} = \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}} \propto \sin(\Phi_{R\perp} + \Phi_S) \frac{\sum_q e_q^2 \, h_{1q} \, H_1^{DiFF}}{\sum_q e_q^2 \, f_{1q} \, D}$$

Not all spin problems have been solved, but enormous progress has been made

The spin-orbiting structure of quarks in nucleons begins to emerge

Theory. Unintegrated PDF and FF play a crucial role; their Q^2 evolution is needed. Factorization and universality issues must be clarified, ...

Experiment. New data from COMPASS (proton target), JLab, RHIC, and GSI. D-Y processes very promising ...